AALTO UNIVERSITY SCHOOL OF ENGINEERING
Department of Applied Mechanics – Marine Technology

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UTILIZATION POTENTIAL OF HIGH STRENGTH STEEL IN FATIGUE LOADED FLOATING PRODUCTION STORAGE AND OFFLOADING UNIT STRUCTURES

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology

Espoo, April 6, 2015

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Floating Production Storage and Offloading units (FPSO) have become a dominant application in deep-water offshore oil and gas fields where building of fixed infrastructure is not cost-efficient option. FPSO may operate continuously on site during its typical 25-year design life without dry-docking. The loading condition especially in the North Sea area is heavy. The aim of this thesis is to study how to utilize potential of high strength steel in fatigue loaded FPSO structures. The scope of this thesis includes the investigation of fatigue critical structural details and what benefits can be obtained.

Achieved fatigue strength improvement by high strength steel with post-weld treatment is investigated by structural hot spot stress method. Long term stress distribution is expressed by Weibull distribution and cumulative damage is calculated based on the Palmgren-Miner’s rule. Five selected fatigue critical details of the FPSO are analyzed. For each detail steel strengths of 235 MPa, 355 MPa and 550 MPa in three reference conditions are investigated. Economic benefits are estimated by cost-benefit analysis based on the results achieved from the fatigue analysis. The estimation of potential benefit is calculated in order to determine economic value.

Typically the use of high strength steels is driven by the weight saving. However, in case of FPSO the obtained weight saving is not the first priority. Instead of weight, cost-savings is reached by keeping the allowable stress range while simplifying the structural geometry. The results indicate that significant decrease for the production costs could be achieved. Secondly, if the local stress concentration exceeds the allowable stress range, fatigue strength of the weld toe regions can be improved by HSS with the weld treatment. Therefore design hours could be saved and expensive modifications can be avoided.

Great potential of the investigated method for local fatigue strength improvement of welded details has been found. Significantly higher improvement was obtained by literature S-N curves compared to the S-N curves given by the classification society DNV. Although, case specific detailed studies are needed to verify the findings since simplified analysis methods and estimations based on the literature have been used. In the future, values during the production should be also measured in order to identify actual benefits.

Keywords Fatigue, FPSO, high strength steel, treatment, weld improvement

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FPSO-aluksista on tullut dominoiva ratkaisu syvänmeren öljy- ja kaasukentille, missä kiinteän infrastruktuurin rakentaminen ei ole kustannustehokas vaihtoehto. FPSO voi tyypillisesti operoida kentällä jatkuvasti koko sen suunnitellun 25-vuoden elinkaaren ajan ilman kuivatelakointi jaksoja. Kuormitusolosuhteet erityisesti Pohjan-merellä ovat erittäin rankat. Tämän työn tarkoitus on tutkia kuinka hyödyntää korkealujuusterästen potentiaalia väsymiskuormitetun FPSO:n rakenteissa. Työn laajuus käsittää väsymiskriittisten rakenneyksityiskohtien tunnistamisen ja mitä hyötyjä tutkitulla menetelmällä voidaan saavuttaa.

Korkealujuusteräksellä sekä hitsin jälkikäsittelymenetelmällä saavutettua väsymiskestävyyden parannusta tutkitaan rakenteellisen hot spot-jännityksen menetelmällä. Pitkänajanjakson kuormitusjakaumaa kuvataan Weibull-jakaumalla ja kumulatiivisen vaurion laskenta perustuu Palmgren-Miner:in sääntöön. Viisi väsymiskriittistä FPSO:n rakenneyksityiskohtaa on valittu analysoitavaksi. Jokaista valittua rakenneyksityiskohtaa on tutkittu teräslujuuksilla 235 MPa, 355 MPa ja 550 MPa kolmessa eri referenssi tilanteessa. Menetelmän taloudellisia hyötyjä on arvioitu kustannus-hyöty analyysilla väsymisanalyysissa saatujen tulosten pohjalta. Arvio hyödyistä on laskettu menetelmän taloudellisen arvon määrittämiseksi.

Korkealujuus teräksiä on käytetty tyypillisesti painonsäästön tavoittelemiseksi. Kuitenkin, FPSO:n tapauksessa painonsäästö ei ole ensimmäinen prioriteetti. Painonsäästön sijaan kustannussäästöjä on tavoiteltu yksinkertaistamalla rakenneyksityiskohtien geometriaa sekä samanaikaisesti säilyttämällä sallitun jännitystason. Tulokset osoittavat, että merkittäviä tuotantosäästöjä voidaan saavuttaa. Toiseksi, jos paikallinen jännityskeskittymä ylittää sallitun jännitystason, voidaan väsymislujuutta parantaa paikallisesti hitsisauman alueella korkealujuusteräksellä sekä hitsin jälkikäsittelyllä. Siten voidaan säästää käytetyissä suunnittelutunneissa ja välttyä kalliilta rakenteellisilta muutoksilta.

Merkittävä potentiaali rakenneyksityiskohtien väsymislujuuden parantamisessa tutkitulla menetelmällä on havaittua. Huomattavasti korkeampi parannus saavutettiin kirjallisuuden arvoilla verrattuna luokituslaitos DNV:n antamiin S-N käyriin. Kuitenkin, yksityiskohtaisia käytännön tutkimuksia tarvitaan tulosten varmistamiseksi, silla yksinkertaistettuja analyysimetodeja ja kirjallisuudesta esiintyviä arvioita on käytetty. Tulevaisuudessa menetelmää pitäisi myös mitata tuotannossa todellisten netto hyötyjen määrittelemiseksi.

Avainsanat FPSO, väsyminen, korkealujuusteräs, jälkikäsittely, hitsin parantaminen

FOREWORD

This thesis carried out as a part of FIMECC BSA – “Breakthrough Steel and Applications” project.

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And finally, cheers to my friends and family for continuous support in my life and studies.

Espoo, April 6, 2015

Jaakko Lappi

Table of Contents

ABBREVIATIONS

ABS	American Bureau of Shipping
CBA	Cost-Benefit Analysis
CL	Centre Line
DNV	Det Norske Veritas
EHSS	Extra High Strength Steel
FAT	Fatigue class
FEA	Finite Element Analysis
FPSO	Floating Production Storage and Offloading unit
HFMI	High Frequency Mechanical Impact
HSS	High Strength Steel
IIW	International Institute of Welding
MAG	Metal Active Gas welding
MIG	Metal Inert Gas welding
NDT	Non-Destructive Testing
NSS	Normal Strength Steel
SCF	Stress Concentration Factor
SHSS	Structural Hot Spot Stress method
TIG	Tungsten Inert Gas welding
QA	Quality Assurance
QC	Quality Control

SYMBOLS

$\Delta\sigma$	Stress range
$Ø$	Diameter
Γ	Gamma function
η	Utilisation factor
A	S-N fatigue parameter
B_T	Net benefit
C	S-N fatigue parameter
C_T	Total costs
D	Fatigue damage
h	Weibull shape factor
K_g	Geometric Stress concentration factor
K_{HSS}	Addition material cost due to use of high strength steel instead of nominal strength steel
K_m	Price of the steel material per ton
K_T	Man-hour cost
k	Number of stress blocks
L	Length of the vessel
l	Length of the component
m	Negative inverse slope of S-N curve
N_D	Number of certain details
N_T	Total number of cycles
n_i	Number of cycles in stress block i
n_0	Number of cycles over the time period for which the stress range level $\Delta\sigma_o$ is defined
q	Weibull scale factor

T_{act}	Draught actual
T_p	Saved time in production
T_{PT}	Time needed for work preparation and transit from hot spot to another
t	Material thickness
T_t	Time needed for the treatment work
T_q	Time used for the Quality Control
R	Radius
S_T	Total savings
W_{HSS}	Weight of the HSS material
W_m	Weight of the saved steel material

1 INTRODUCTION

1.1 Background

FPSO is a floating production, storage and offloading unit. Since 1974, when the first FPSO was installed in Ardjuna oil field in Indonesia, the floating production system has become a dominant solution for deep water offshore fields. The fixed pipeline infrastructure is not a cost-effective solution for the deep water fields as a result of long distance from shore and great water depth. In the mid-80s, the discovery of new giant oil fields such as Albacora and Marlin at the coast of Brazil were pushing oil companies to investigate new solutions. The main driver was how to utilize natural resources rapidly, from water depth greater than 1000 feet. [1] Today the offshore industry is forced to even greater water depths in order to discover new oil fields. In year 2030 deep water oil fields are estimated to produce already 45 % of total amount of produced oil globally. [2] Deep water activities started the new era of the floating drilling and production units. Advantages of the FPSO for the deep water were recognized in the mid-90s and it started a significant growth of the FPSO worldwide fleet. The fleet is constantly increasing and the most likely forecast for the five year period 2013-2017 is 110 new orders. [3]

With the FPSO, various field layouts types and combinations with other facilities can be applied. One example of the FPSO based oil field layout is presented in Figure 1. Pumped crude oil from several wells can be stored in separated cargo tanks in the FPSO, to realize best the possible price in current market conditions. [4]

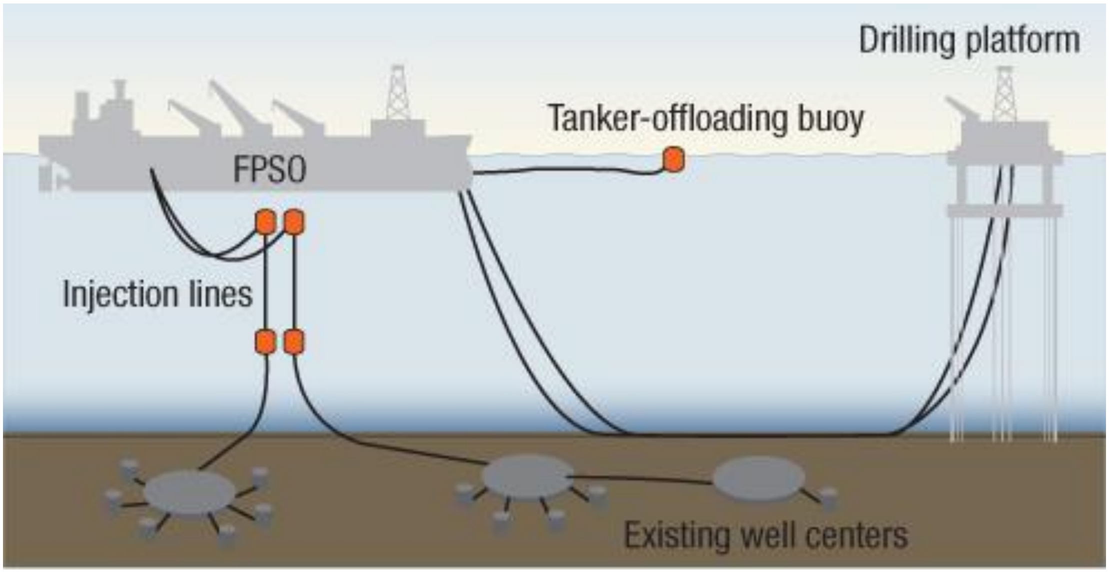


Figure 1. Example of the oil field layout with the FPSO. [5]

Compared to fixed offshore structures, the total time cycle of design and construction of one FPSO is shorter. Therefore the owner will receive early cash flow from the oil field, which is a significant benefit. [6] FPSO can be also relocated easily compared to fixed offshore structures, which is a significant advantage for the owners. Many existing crude oil tankers have been converted to FPSOs. The conversion has significant cost and schedule benefits compared in to newbuilding FPSO. [7] However, loading conditions at the site define strength and fatigue requirements, which can significantly differ from tanker design loads. In addition, all systems related to production such as topside modules and turret are increasing the weight of the vessel. Therefore a lot of modifications are needed to meet operational and structural strength requirements in case of conversion.

Typical operational life time is up to 25 years and there are many high-risks related to FPSO operations and systems. FPSO is moored to operation site for several years without scheduled dry-docking intervals that ships have. [7] All types of failures in structures or operation systems can cause serious environmental and life-threatening consequences. As we have seen in the past, offshore accidents may lead to catastrophes. Latest major offshore catastrophe in 2010 at Gulf of Mexico claimed 11 people and caused estimated oil spill of 4.9 million barrels as a result of explosion and sinking of *Deepwater Horizon* oil rig. [8] On February 2015 FPSO unit *Cidade de São Mateus* was hit by an explosion causing nine fatalities and several injuries at offshore Brazil. No environmental impacts were reported. [9] As a result of high risks, the safety and structural reliability are a primary concern for all oil companies today. As well the interruption in the production is leading for significant economic losses.

Until today, the welding is the primary joining method of marine and offshore structures. One of the known structural failure modes related to welded structures is fatigue. Cyclic loads induce fatigue failures. They typically initiate from geometrical discontinuities such as welded joints. [10] For ships, structural inspections can be provided periodically while dry-docking, and all structural failures can be repaired. However, due to long dry-docking intervals and high-risks of operations the case is different for FPSOs. Design has to perform high level of onsite reliability. Therefore, special attention has to be paid for the fatigue design as well.

New materials, design methods and welding techniques are investigated continuously to improve current design practises and meet future requirements. A lot of research related to advanced production techniques and materials has been done. In the fatigue design the focus has recently been on High Strength Steels (HSS), weld quality and post-weld treatment methods. Results have been promising in terms of fatigue strength of the welded structures. Even significantly higher than current design values. [11] [12] [13] [14] However, the utilisation of new high strength steel materials in structural design of FPSO structures has been very limited.

1.2 Scope of research and limitations

The aim of this thesis is to study how to utilize the potential of high strength steel in fatigue loaded FPSO structures. The scope of this thesis includes the investigation of; what are the potential structural details and what are the benefits that can be obtained. In addition, the estimation of potential benefit is calculated in order to determine economic value.

First, the state of art review presents backgrounds and current classification practices related to the fatigue design, High Strength Steels (HSS) and post-weld treatment methods. Research results from the literature achieved for the welded specimens made of HSS base material are used and compared to the classification rules. In Chapter 3 analysis procedure is presented and selected fatigue critical details of the FPSO are presented in Chapter 4. Three different types of details for the fatigue analysis are selected. Furthermore, two geometry optimized designs of one detail are investigated. Hence, totally 5 details are analyzed. Three different steel strengths and reference conditions for each detail are investigated. Fatigue strength comparison is done in Chapter 5. Cost-benefit analysis is done for the geometry optimized designs in Chapter 6. Estimation of potential net benefit is calculated and discussed in order to determine economic value. Finally, discussion and conclusions are presented.

In the scope of this thesis available research results and classification data are utilized. Investigated objectives are limited for the structural details of ship shaped FPSOs. Since the most fatigue critical structural details are investigated, it is expected that only full penetration welds are applied. Therefore cracking from weld root can be excluded as it is not the most likely failure mode. Low Cycle Fatigue damage factor is expected less than 0.25. Therefore fatigue strength improvement in the low cycle fatigue case is not investigated. [15] The improved fatigue capacity of welded connections may lead to designing higher nominal stress level which may cause side effects such as strength and/or buckling criteria to become governing or cracking from the base material become first likely failure mode. Studying such side effects in scope of this thesis is excluded.

2 STATE OF ART

2.1 FPSO structure

In the early stage of FPSOs when there were no specific structural design methods and classification rules for them, the existing rules of trading tankers were applied. However, several differences between FPSO and trading tanker can be identified. Today FPSOs can be classified for site specific environments while trading tankers are commonly classified for North Atlantic conditions. Loading and offloading cycles for FPSO are more frequent and larger variety of load amplitudes occurs. Tankers operate in ballast or fully loaded condition whereas an FPSO changes its loading condition constantly. FPSO has continuous site operation without dry-docking, while ships are normally docked in five year intervals. The hull girder design bending moment of FPSO is based on 100 years significant wave height while it is 20-25 years for trading tankers. [16] [4] These backgrounds determine the unique requirements for the structural design of FPSOs.

FPSO consists of two main parts; a hull and a topside. Hull structure includes the hull and a turret. Topside structures are production modules and their supports, helideck and accommodation module; see Figure 2. Topside structures are laying on the supports, approximately 3-4 meters above the main deck level to provide sufficient natural air ventilation and protect production modules from green water. Large cargo tanks for the oil are located inside of the hull and divided into several sections.

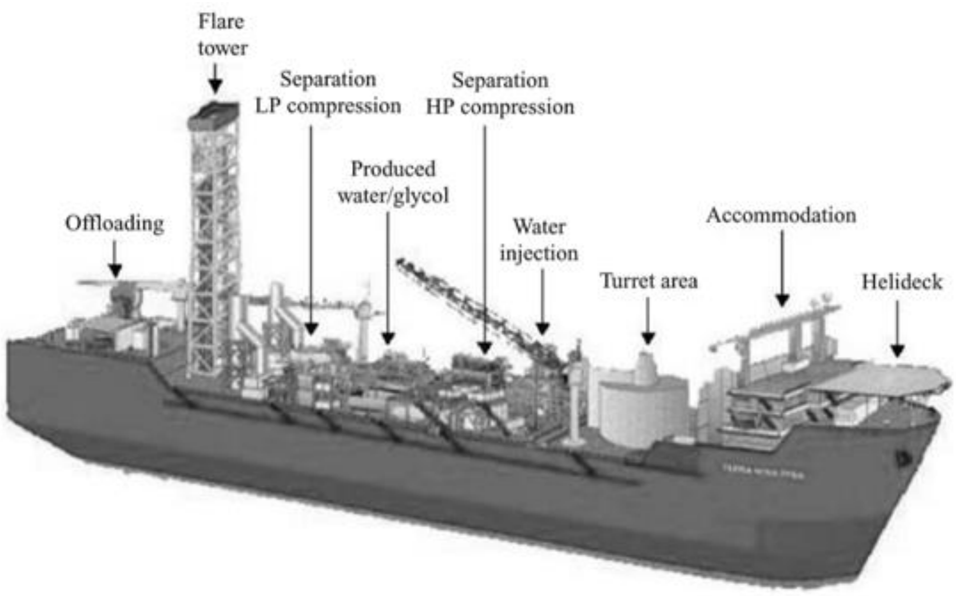


Figure 2. Typical ship-shaped FPSO with internal turret. [4]

The hull structures of the FPSO are of primary importance due to fact that they are carrying all internal and external loads. Topside structure does not participate in the ship girder strength. Hull structure can be divided into three levels; primary (hull girder), secondary (web frames and girders) and tertiary (beams and plates) structural levels. As a result of the loads, deformation such as hull bending and stiffener bending occurs in the structural members. The load carrying system of the hull has similar longitudinal framing that is used in trading tankers as well. Double sides are required by classification society to protect against possible collision.

As stated earlier, welding is used as primary joining method in the structures. Stress concentrations at the welded details are known as potential crack initiation locations. Several welded, fatigue critical joints in the FPSO structures exist. Critical connections can be identified for example from interfaces between main deck and topside structures, longitudinal connections to transversal members, crane pedestal connection to hull and hopper knuckle area. [17] Therefore, a special view should be put on these details in the fatigue strength assessment.

However, the structural reliability is not only dependent on the design. There are several other factors such as fabrication quality, operations, maintenance and inspection, that are affecting the structural reliability as well. As a result of high reliability requirement, FPSOs have to be fabricated with higher standards than trading tankers. [4]

2.2 High Strength Steels in offshore structures

The material selection for the marine and offshore structures is always a cost-benefit question, nevertheless, having limiting values such as strength, stiffness and fracture toughness. Hence, a functional requirement of the particular design is the key for the material selection. [18] Other important factors are manufacturing aspects such as weld-ability and forming, weight of the material, fatigue strength, corrosion resistance, toughness and vibration. Until today, most commonly used steel material, Normal Strength Steel (NSS) has the yield strength of 235 MPa. The use of steel with greater yield strengths is increasing in marine and offshore applications. The use of High Strength Steels have been driven by weight and cost saving benefits. Depending on the context, the definition of High Strength Steel (HSS) may vary. In offshore context the definition of HSS is the yield strength greater than 235 MPa.

As a result of increased experience and identified benefits of HSS, already steels with yield strength of 500 MPa – 800 MPa have been utilized in offshore installations such as drilling jack-ups. [19] However, most of installations are being dry-docked in 5-year intervals. Hence, the possible fatigue failures can be inspected and repaired. For floating production units the periodic dry docking inspection is not possible and hence, more careful attitude towards HSS has been taken.

The fatigue strength of the welded structures made of HSS is under high interest today. Fatigue tests are time consuming and expensive. Therefore quite limited amount of data is available today. The stress distribution that FPSOs are encountering is quite unique. For the valid fatigue test data corresponding variable amplitude loading should be used. Some test data can be found and they are presenting a good performance when the quality of the weld is high enough.

Manufacturing processes and quality have high requirements when High Strength Steels are applied. One of the main issues related is weldability and the quality of welded joints. [12] It has been recognized, that post-weld treatment methods are needed in general to improve the quality of welded joints made of HSS. Therefore, additional work and focus for the quality are required. However, there are a lot of questions and clarification needed related to new steel materials and fabrication techniques. For example the microstructure of high tensile strength steel is metastable. Large heat input can deteriorate mechanical properties which may cause failures at the weld seam areas. [20]

Classification rules have notes related to steels with high yield strength. HSS has increased fatigue strength in the base material compared to NSS. Therefore Classification society DNV gives reduction factor for the derived stress range if HSS is used as a base material. [15] The increase of the fatigue strength of welded connections is not taken into account if post-weld treatment is not used. With the post-weld treatment methods DNV gives improvement factors on fatigue life for welds made of HSS base material. In general, HSS offers relatively small additional benefits into the fatigue design under current classification practise.

Classification rules are typically quite slow for changes. However, the first step of approval for the increased fatigue strength for steels with high yield strength has been taken and based on the literature, more acceptable aspect in the future can be expected.

2.3 Fatigue loads

FPSOs are affected by various types of external and internal loads. Two types of loads can be identified; static and environmental loads. [16] Static loads are known as still water loads that occur as a result of buoyancy and weight of the vessel. Global vertical bending moment and shear force in the hull girder are caused by still water loads. Still water loads may vary during operation as a result of change of buoyancy, cargo, ballast water, riser tension and personnel. In terms of fatigue of FPSO, the major static loads are cargo and ballast water loads. They have large amplitude, however, number of cycles is relatively low.

Environmental loads are caused by waves, wind, ice, current, slamming, sloshing etc. In some cases temperature and snow may be important as well. Environmental loads induce responses such as vertical and horizontal global bending moment, global shear force, external sea pressure distribution and accelerations. In some cases, also global axial force and torsional moment may occur. Typically marine structures are subjected to a combination of different types of loading and directions of waves. However, freely weathervaning FPSO is encountering waves with a zero angle, fore ahead. Therefore the number of fatigue load cycles caused by vertical bending moment is large. [21]

Environmental loads are related to the weather conditions of the site area. If the operational area for the whole design life time is not known, the conditions of North Atlantic are used for the worldwide operating range. [22] However, area specific wave scatter diagrams are commonly used when specific operation site for the life time of vessel is already known. Transit condition, which means all movements at the sea from one location to another, has to be taken into account as well. [23]

The main difference between fatigue and ultimate loads are that fatigue loads are affecting cumulatively. [10] Fatigue is a material failure caused by time varying stresses. A fatigue failure is caused by millions of load cycles of stress below the yield limit of the material. [10] One fatigue crack at the critical section may cause a serious risk and in worst case it may crack the whole hull of the vessel. Three main phases of the fatigue process can be identified; crack initiation, crack propagation and final failure. [24] The fatigue failure starts from the very small crack and grows until it extends through the material thickness if the loading is continuing. All discontinuities in the structures that are causing local stress concentrations have an adverse effect for the fatigue strength. [10] [24] Fatigue causes local failures which may be difficult to notice from complex structures.

Assessment of the fatigue strength of the welded structures requires a relevant stress distribution. As a result of irregular waves the FPSO is subjected to variable amplitude loading during its life time in the offshore oil field. Variable amplitude loading resulting irregular stress fluctuation with variable magnitude stress ranges. [25] Stress range for the fatigue analysis can be defined from long term stress histogram; see variable amplitude load histogram in Figure 3. Long term distribution of loads for fatigue analysis can be estimated by using wave scatter data which is used with the hydrodynamic analysis to calculate responses. A Weibull distribution is found to describe this long term load distribution well. [15] Therefore it is used in simplified local fatigue analysis.

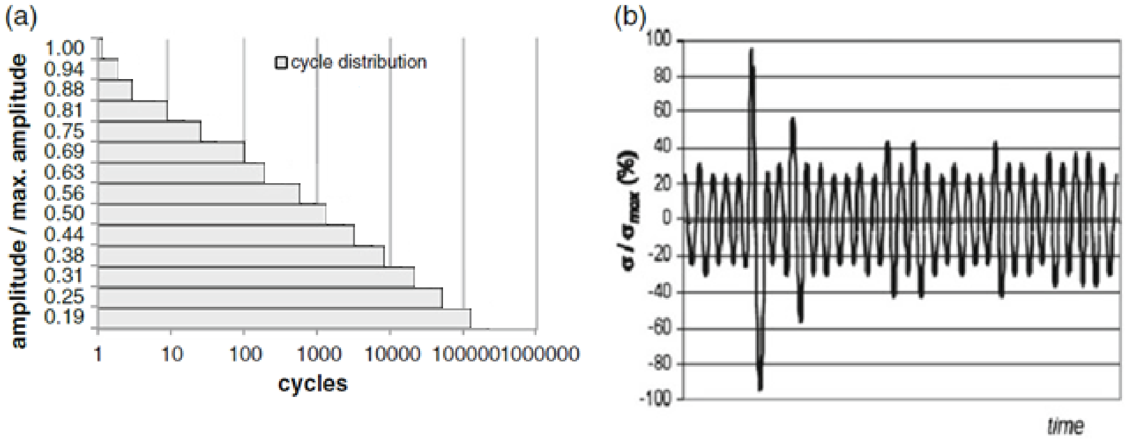


Figure 3. Example of the load histogram, modified from [26]. Distribution of fatigue load cycles (a) and load spectrum (b).

Normally, loads having less than 10000 cycles during the life time are understood as low cycle loads and loads having more than 10000 cycles as high cycle loads. [25] Cargo loads, including the still water loads, are causing low cycle fatigue damage as a result of cargo loading and offloading. [24] Wave loads are directly generated by waves that the hull is encountering and they are causing high cycle fatigue damage. Magnitude of the wave loads is depending on the site area. Other loads that have an influence for the fatigue life are transient loads such as thermal stresses, vibration loads and impact loads.

At the early design phase, it is important to recognize these fatigue loads and fatigue critical structural details, where the fatigue failure may occur. Each ship and offshore vessel type has different fatigue critical areas and structures related to the vessel type. Nevertheless, commonly these structural sections consist of similar and standardised details such as stiffened plates, brackets and stiffeners.

In addition to the fatigue design, also production methods and quality have a high influence for the fatigue capacity. Weld defects such as undercuts, angular distortions, axial misalignment, and lack of penetration or porosity are potential crack initiation locations and known to reduce the fatigue life. Also the corrosion reduces fatigue life, unless structures are well protected against it. Welds are producing a change of shape in the base material as well, which is causing stress concentrations. The stress concentration occurs at the weld toe and root which are typical areas where cracks can occur. Typical crack locations are presented in Figure 4.

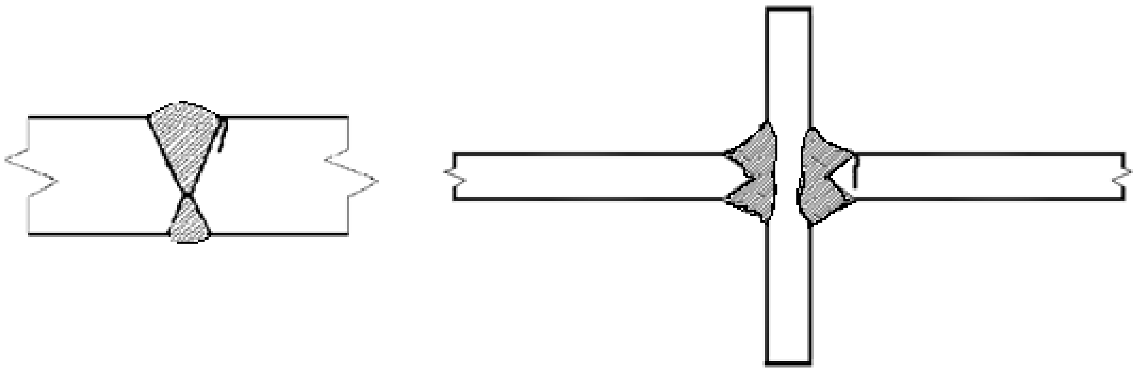


Figure 4. Typical crack location for the full penetration butt weld (left) and T-joint (right).

First level fatigue capacity improvement of fillet or partial penetration weld is to use full penetration weld. As a result of good fatigue capacity, full penetration welds are used at the connections of the most fatigue critical structures. This thesis is focused to investigate the fatigue critical details of FPSO. Therefore it is limited only for the case of full penetration welds and condition when the weld root side failure is not the most likely failure mode. Since full penetration welds are used post-weld treatment methods can be applied for the fatigue strength improvement.

2.4 Fatigue assessment

The fatigue assessment is based on the conservative prediction of the ranges of cyclic stresses during FPSOs life time. [25] Several methods to assess fatigue strength exist. They are applied for different types of structures and structural details. They differ in many terms such as amount of work, accuracy and level of simplifications.

S-N fatigue approach is commonly used to assess the fatigue strength of the welded structures and base material. S-N curves represent the relation between the fatigue life and alternating constant amplitude stress acting at the welded joint or base material. The design S-N curves are based on the mean-minus-two-standard-deviation curves for relevant experimental data. They are associated with a 97.7 % probability of survival. [25] In 1982 Munse introduced standard S-N curves for fatigue design of several actual marine structural details. [27] Basic design S-N curves are made for as-welded joints which means the condition of welded joint after welding prior to any subsequent treatment. S-N data for improved weld joints can also be found.

In addition to the S-N fatigue approach, other methodologies that may be used are fracture mechanics or prototype testing. Prototype testing is the most direct way to assess fatigue life for a structural detail. However, it is very expensive and in practise not cost-effective method. Fracture mechanics method can be used in case of unusual structural detail, when it is not covered by experimental S-N curves. Experimental S-N curves are determined by small scale fatigue test which is relatively less expensive method.

For the S-N curve approach, three different stress approaches exist to assess the fatigue strength of the structural detail; nominal stress, hot spot stress and notch stress approach, see Figure 5. [28]

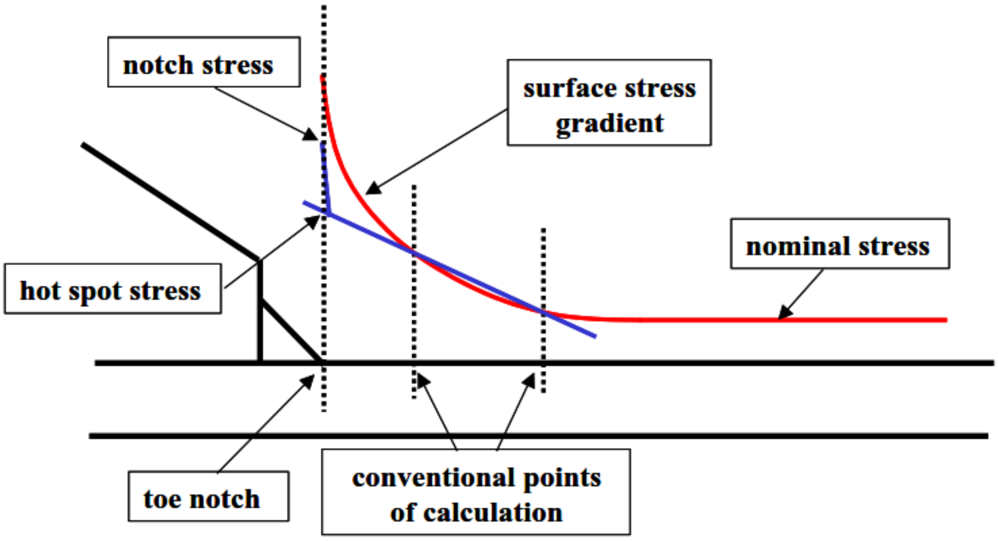


Figure 5. Stress definitions at the weld toe. [28]

Nominal stress is the membrane stress which can be determined by the classical beam theory whereas hot spot stress can be understood as a geometric stress taking into account the effect of structural geometry, excluding the weld toe shape. Notch stress corresponds to the fatigue effective stress at the weld toe. It is defined as a combination of stress due to detail geometry and the non-linear stress due notch at the weld toe. Correct S-N curve have to be used according to the stress method. [28] [15] For the notch stress approach only one design S-N curve exits since the effects of structural geometry and weld geometry are both accounted by calculated stress. For nominal stress and hot spot stress approach several design S-N curves are determined for different joint classes.

Stress concentrations due to structural geometry can be expressed with Stress Concentration Factors (SCF or *K*-factor). Nominal stresses can be transferred to hot spot stresses with the SCFs. Therefore, the relation between the hot spot stress and nominal stress is:

$$\Delta\sigma_{hot\ spot} = \Delta\sigma_{nominal} \times SCF \tag{1}$$

Where $\Delta\sigma_{hot\ spot}$ is the hot spot stress range, $\Delta\sigma_{nominal}$ is the nominal stress range and SCF is the stress concentration factor. SCF is used in the fatigue design as a correction factor for the local stresses due to structural geometry.

For instance, classification society DNV has determined geometric stress concentration factors for common structural details; see Figure 6 as an example. Separate SCFs are given corresponding to axial and bending loading conditions. The factors have been determined based on Finite Element Analysis (FEA) of actual geometries. SCFs for certain detail can be determined by FEA if factors given by classification society are not used.

Table A-2 K-factors for stiffener supports (Continued)

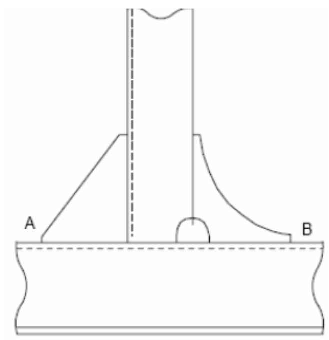
No.	*Geometry*	*Point A*		*Point B*	
		K_g *axial*	K_g *bending*	K_g *axial*	K_g *bending*
12		1.60	1.80	1.27	1.27

Figure 6. Stress concentration factors for standard stiffener support details given by classification society DNV. SCFs are given for axial load and bending loading condition for hot spot locations A and B. [15]

Brackets presented in the Figure 6 are simple shape bracket (left side) and soft nose bracket (right side). They present standard geometries that are commonly used in shipbuilding. However, in high fatigue loaded cases the geometry may need to be further optimized for fatigue and advanced geometries are needed.

The International Institute of Welding (IIW) gives standard design S-N curves; see Figure 7. The fatigue life is represented as a number of constant amplitude load cycles N to failure and the variable S represents the applied nominal stress range.

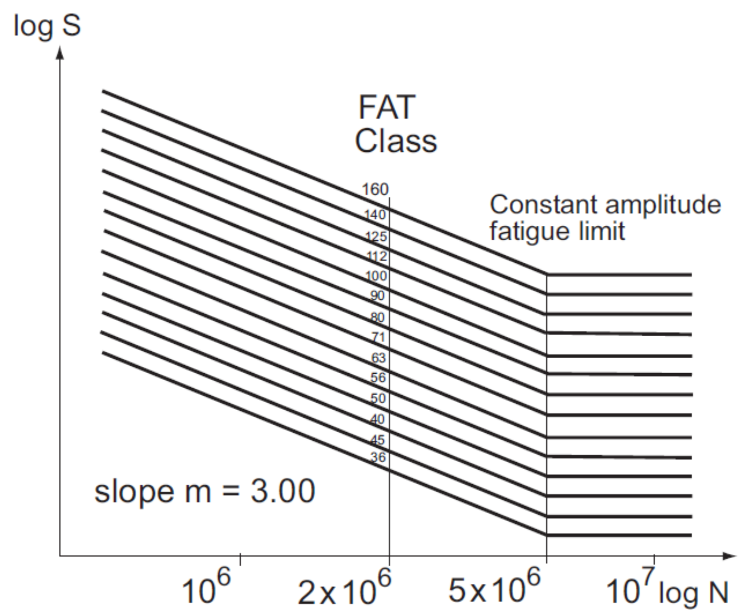


Figure 7. IIW standard S-N curves. The logarithmic scale of magnitude of cyclic stress (S) is presented against the logarithmic scale of cycles to failure (N) [24].

The equation for particular design S-N curve can be written:

$$S^m N = A \tag{2}$$

where *S* is stress range, *m* is negative inverse slope, *N* is fatigue life in number of cycles and *A* is a fatigue constant.

Fatigue classes (FAT) present the fatigue strength of the detail in terms of nominal stress corresponding to 95 % survival probability at 2 x 10^6 cycles to failure. Standard quality of welding is referred for FAT classes. [29]

All significant stress ranges that may cause a fatigue failure should be considered. [25] For the variable amplitude loading 2-slope, bilinear S-N curves are used. S-N curves for different weld joint types in air and in seawater with catholic protection are given in the classification rules; see S-N curves in air by DNV in Figure 8. In region $N \leq 10^7$ cycles the slope $m = 3$ and in region $N > 10^7$ cycles the slope m = 5 is applied.

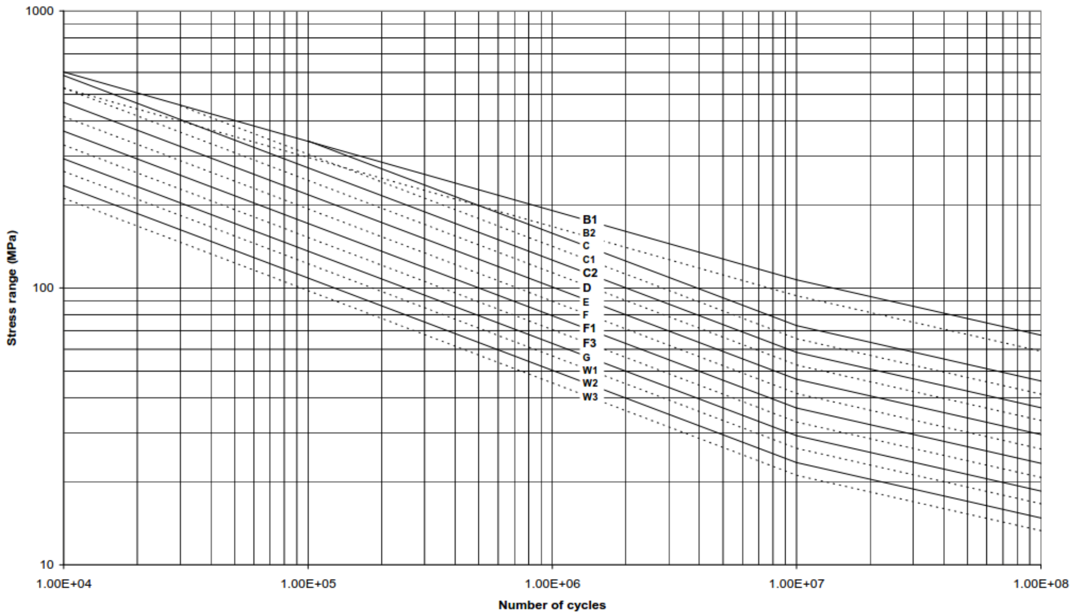


Figure 8. S-N curves for different weld joint types in air defined by DNV. [25]

S-N curves may be linearly extrapolated for lower number of cycles (less than 10 000 load cycles) if needed. However, significant yielding at the hot spot area appears which affects non-linear material behaviour. For the FPSO low cycle fatigue may be an issue to consider in some local areas due to loading and unloading cycles.

Cumulative damage under variable amplitude loading is calculated by S-N approach and assumption of linear cumulative damage. [15] [25] Palmgren-Miner's rule is applied. Accumulated damage is calculated for each load cycle at different stress range by following equation:

$$D = \sum_{n=i}^{k} \frac{n_i}{N_i} \tag{3}$$

where D is the accumulated damage, k is the number of stress blocks, n_i is the number of cycles in stress block i and N_i is number of cycles to failure at constant stress range. Long term distribution of stresses can be described by Weibull distribution.

Hull of the FPSO is large and complex structure which has thousands of steel parts and hundreds of kilometres of weld seam. The fatigue design of such complex structure is never simple. [24] In FPSO conversion projects the fatigue and strength design is especially challenging. In the conversions the old hull structure has already accumulated fatigue damage and therefore, life extension may be needed.

2.5 High fatigue capacity welded joints

The relation between increased yield strength of the base material and the fatigue strength has been investigated for the last 40 years, since they have been commonly used in ship structures. Since the fatigue of welded joints is essentially a crack growth phenomenon, it has been stated that the fatigue capacity for the welded joints is nearly independent of the yield stress of the applied steel. [24] Therefore, same design S-N curve is commonly used for the fatigue strength assessment of the welded structures regardless of the yield strength of the base material. However today, improvement of the welding technology and the latest research on the fatigue phenomenon have presented promising results for fatigue capacity of welded joints when the quality of the welds is high.

There are many drivers to improve the fatigue performance and reduce the fabrication costs of welded structures. Nowadays, a wide scope of High Strength Steels and fatigue strength improvement methods are available. However, it is not very clear if any benefits can be obtained at the design phase. Experimental tests have presented that good fatigue performance for welded joints can be obtained. [12] [11] [13] [14] The fatigue life of tested specimens is considerably higher than currently rules are expecting. However, there is very limited amount of data available how it will affect for fabrication costs compared to currently used methods at the shipyards.

2.5.1 Review of welding methods

In shipbuilding the quality of the welds has typically not been the main concern, large safety margins are used instead. At the shipyards, traditional arc welding methods such as MIG and MAG welding are still widely used since they are very suitable for the shipyard work. Automation, robot technology and advanced welding methods have become more common as well. For example, at assembly lines advanced automated welding methods can be used. However, due to very complex geometries it is assumed that robotic welding methods cannot replace traditional manual welding methods completely in the shipyard practice. [30]

Steel manufacturers have spent a lot of efforts for the weldability of the High Strength Steels. In practise, the welding of the HSS is not more difficult than NSS. Same welding processes can be used. Nevertheless, HSS is much more sensitive for the correct consumables and welding parameters. Hence, Quality Assurance (QA) and Quality Control (QC) are playing an essential role. In addition to superficial inspection, the quality of the welded joints can be analysed by non-destructive testing (NDT). Classification societies require NDT tests to be done for some particular connection in order to ensure the structural safety.

Not all potential of the fatigue capacity that High Strength Steels offer is not possible to capture by traditional arc welding methods. Techniques such as laser welding and laser-hybrid welding induce less crack-like defects into welds than traditional methods. The laser-based welding techniques have lower heat input, which results in smaller distortions of the plate. Therefore they are noticed as a promising technique to produce welds with the high fatigue capacity. However, sufficient fatigue strength improvement can be obtained by arc welding methods as well. [31] [14]

2.5.2 Fatigue strength improvement

Fatigue strength could be improved by various techniques. However, all of them may not be feasible in the shipyard practice, FPSO loading condition or from the economic point of view.

The improvement of weld toe geometry is not increasing the fatigue strength, if the fatigue failure from the weld root is the first failure mode. This thesis is focusing on the fatigue critical, full penetration welded joins where weld root side failure is not the most likely failure mode. [15] [25] Hence, the weld geometry improvement methods can be considered as well.

Classification of different post-weld treatment methods is presented in Figure 9. Methods can be divided into weld geometry improvement methods and residual stress methods. [14]

Weld geometry improvement methods	***Machining methods***		Burr grinding
			Disc grinding
			Water jet gouging
	Remelting methods		TIG dressing
			Plasma dressing
			Laser dressing
	Special welding techniques		Weld profile control
			Special electrodes
Residual stress methods	***Mechanical methods***	***Peening methods***	Hammer peening
			Needle peening
			Shot peening
			Ultrasonic peening
		Overloading methods	Initial overloading
			Local compression
	Thermal methods		Thermal stress relief
			Spot heating
			Gunnert's method
			Low temperature transformation electrodes

Figure 9. Classification of weld improvement techniques that can be used in marine applications. [14]

The fatigue capacity of the welded joint is highly dependent on the weld geometry, especially when having the HSS as a base material. [19] Poor geometry or defects such as undercuts can significantly reduce the fatigue capacity of the welded joint. Geometry of weld can be improved by adjusting the shape of the seam and removing weld defects, which are known as initiation sites for fatigue cracks. Improvement of the weld geometry reduces local stress concentrations on weld joint area as well.

Similar results have been achieved in many investigations which have been done for as-welded conditions. For example INDUCWELD [13] and Fricke et al. [11] have investigated welded joints made of HSS base material in as-welded conditions with different welding methods. The results indicate that the quality was not sufficient to receive full potential of the HSS. Only small improvement of fatigue strength was obtained.

However, when the weld quality is prioritized, results have been much more promising. A few different improvement methods have been investigated by Costa et al. [12] Fatigue strength tests have been made for the DOMEX 600 DC steel manufactured by SSAB. The steel has yield strength of 670 MPa and a tensile strength of 750 MPa. Three different conditions for MAG welded butt joints were tested; as-welded; weld overfill removed by grinding; and welds overfill and first weld root removed by grinding. Results are presented in Figure 10.

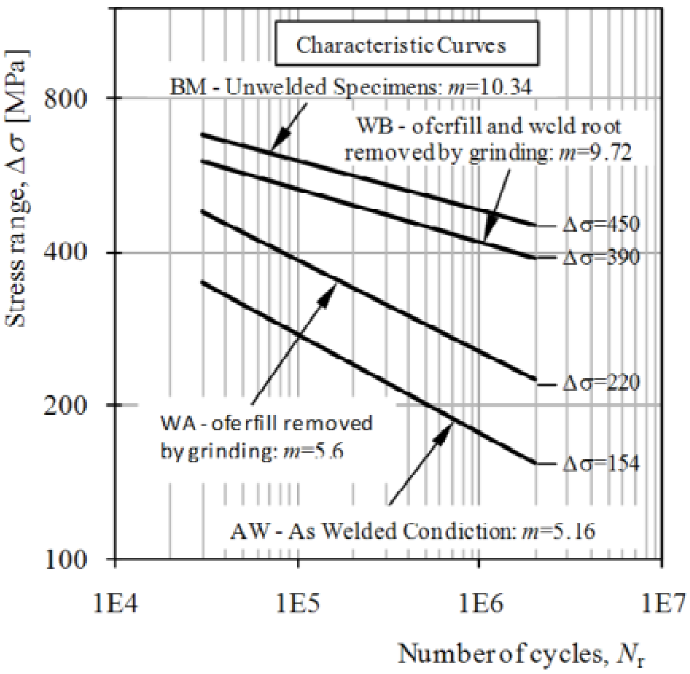


Figure 10. Comparison of S-N curves based on experimental study of three different conditions and base material [12].

The most significant improvement for the fatigue strength was obtained by the treatment method where overfill and weld root of the first weld were removed by disc grinding. The improvement of the fatigue strength was obtained as a result of reduced level of initial defects. When the post-weld treatment was used, the fatigue strength of the welded joint in the most beneficial case is close to fatigue strength of unwelded specimen of the base material. Compared to the as-welded condition, increase of 150 % on the fatigue strength was measured; even the fatigue strength of the as-welded condition is higher than recommended by IIW. [32] That is a significant improvement compared to current classification fatigue design rules.

The other post-weld improvement category is the residual stress methods which induce a local plastic deformation by mechanical or thermal methods. They can either create a region of beneficial compressive residual stresses or to reduce the level of residual tensile stresses from weld. [14] Peening methods such as high-frequency mechanical impact method (HFMI) are presented to be very effective fatigue strength improvement methods.

Yildirim, Marquiz et al. [26] [33] [34] [35] [36] have done studies related to the fatigue strength of welded HSS base material joints treated by HFMI-method. The results presented significant improvement compared to IIW fatigue standards. Based on the results, the new FAT classes have been proposed; see Figure 11 for Structural Hot Spot Stress (SHSS) approach.

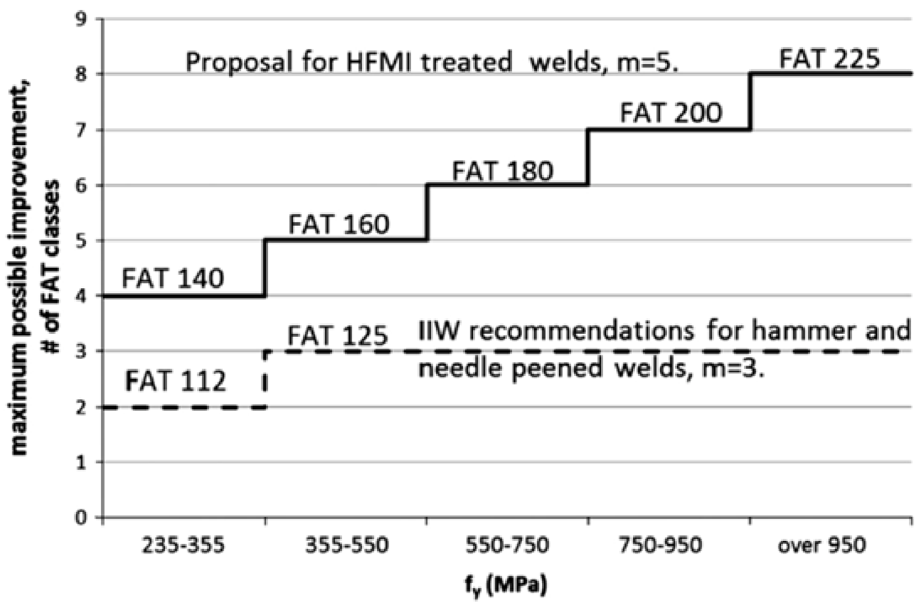


Figure 11. Proposal for the new fatigue classes for HFMI treatment method for Structural Hot Spot Stress (SHSS) approach. [33]

Compared to the IIW standard fatigue class FAT 90 for as-welded condition the results present more than 50 %, and up to 150 % higher fatigue strength depending on the yield strength of the base material. [37] Fatigue test were made both under constant and variable amplitude loading. It was found that in the test made under variable amplitude loading the local stresses at improved weld toes are significantly higher. Local yielding is expected and beneficial compressive residual stresses may be reduced. It was also stated that constant amplitude loading may give over-optimistic results for the improved welds. Therefore it is important that relevant load spectrum is used.

In the other publication by Yildirim and Marquis [26] HMFI-treated weld joints made of S700 HSS base material were tested under variable amplitude loading; see Figure 12. Four HMFI-tools by different manufacturers were investigated.

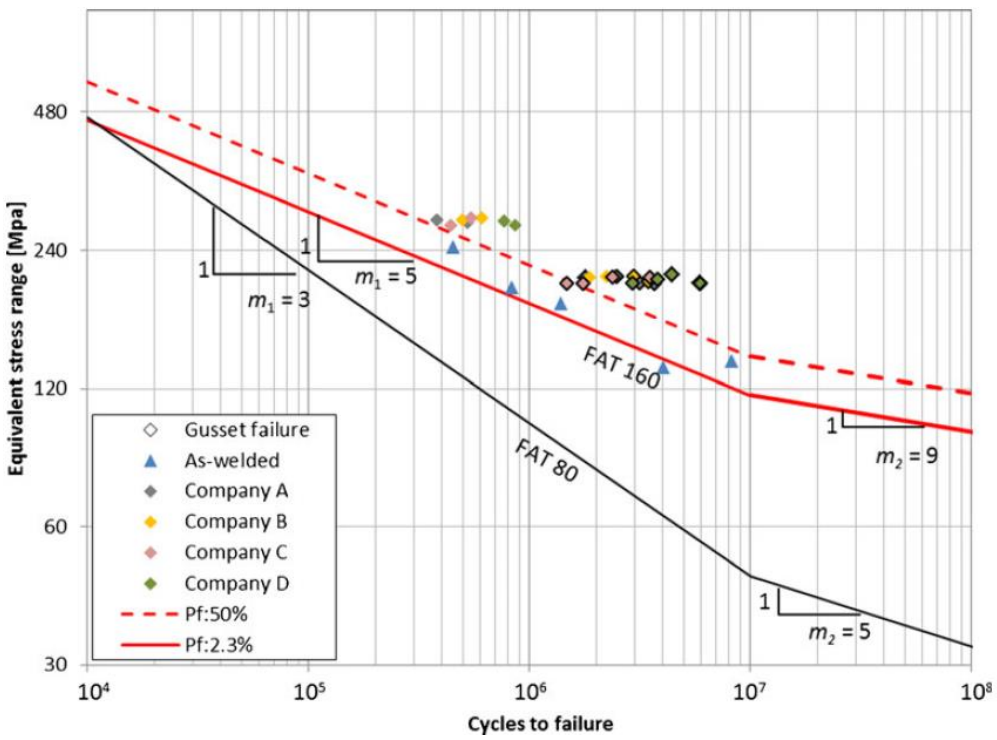


Figure 12. Fatigue test results for the HFMI-treated welds subjected variable amplitude loading. [26]

Fatigue test results from each four different tools are promising and indicate the expected performance. None of the data points for the improved test specimens are below the expected mean fatigue strength line FAT 194 and significantly above the previously proposed FAT 160 by Yildirim and Marquis. [34]

As a result of treatment work to be done, the post-welding treatment methods will increase the production time and therefore the production costs as well. Time used for the treatment varies in wide range based on the reference. Steel yield strength has also impact for the treatment time. Kirkhope et al. [38] have estimated the additional work of post-welding treatment methods. Three methods were investigated; hammer peening, burr grinding and TIG-dressing. The used operational factor is hours per each one meter of weld seam. It was examined that burr grinding was the least additional work requiring technique with 0.10 h/m of additional work. For TIG-dressing 0.13 h/m and for hammer peening 0.20 h/m additional work was determined. Jármai et al. [39] presents ranges of 0.1 – 1.0 for burr grinding, 0.07 - 0.2 h/m for hammer peening and 0.06 - 0.09 h/m for HMFI treatment. However, since the treatment is done very locally for a short distance at the hot spot location treatment time will remain short.

Main challenges related to weld improvement methods in practise are quality assurance of the welding process and inspection. Some of these methods are already widely used in certain industries where quality control is less challenging, and therefore more sophisticated. [38] As a major priority, it should not be forgotten, that the design has the most significant influence on the fatigue strength. Poor geometrical design of the structure cannot be compensated by fatigue strength improvement techniques. Improvement methods such as hammer peening and TIG-dressing should be taken as additional improvement methods, which can improve the fatigue strength of existing, already good design.

2.5.3 Fatigue design of improved welds

Regulatory framework of FPSOs depends on local regulations on site area and owner's philosophy. Operating at the offshore oil field requires fulfilling rules and regulations of the country that is having legal rights for the sea area. Rules of several national and international authorities may have to be followed. In addition, rules of the classification societies and flag state are commonly followed as well. [4] In scope of this thesis, the rules of classification society DNV GL are applied. However, as classification rules of new joint venture classification society DNV GL is not widely available, latest rules of DNV are used. Classification societies are widely referring to IIW in fatigue design. IIW is giving recommendations for the fatigue design of the welded joints, although no rules or code of practices.

For a long period FPSOs were considered as trading tankers in terms of guidance and classification. Nevertheless, several differences between FPSOs and trading tankers exists. [4] When the world's FPSO fleet was continuing its growth, the classification societies set up specific rules for FPSOs to respond unique vessel type and operations that they present.

DNV has released its first rules for classification specified for FPSOs in 2001. Up today, there are several guidance, rules and regulation to follow. They are primarily concerning marine systems and structural issues, such as hull. Design principles of offshore structures are based on safety operation during transport and site operation. Loads presenting worst possible loading scenarios are used for design. As earlier figured out, FPSOs can be classified for worldwide or site specific conditions where site specific conditions are commonly applied. [23]

Recommended Practice for the fatigue design of offshore steel structures by DNV [25] is valid for steel materials with yield strength up to 960 MPa in air and up to 550 MPa in seawater with cathodic protection. In DNV's Offshore Standard, three categories of steels have been defined according their yield strength; NSS with 235 MPa, HSS with 265-390 MPa and Extra High Strength Steels (EHSS) with over 420 MPa yield strength. [40]

However, even if steels with high yield strength are accepted by DNV, the yield strength of the base material has no relation for the used design S-N curve for welded joints if post-weld treatment is not used as well. DNV gives design factors for improvement of the fatigue life by fabrication. The referred methods are hammer peening, TIG-dressing and weld toe grinding; see Table 1.

Table 1. DNV's guidance for improvement on fatigue life by different fabrication methods. [25]

Improvement method	*Minimum specified yield strength*	*Increase in fatigue life (factor on life)*
Grinding	Less than 350 MPa	$0.01f_y$
	Higher than 350 MPa	3.5
TIG dressing	Less than 350 MPa	$0.01f_y$
	Higher than 350 MPa	3.5
Hammer peening	Less than 350 MPa	$0.011f_y$
	Higher than 350 MPa	4.0

Based on the DNVs guidance, the highest fatigue strength improvement is obtained by hammer peening method. The yield strength of the base material has a relation to the improvement of fatigue life as well. However, for the steels with yield strength greater than 350 MPa the factor on life is constant; see Figure 11. Improved D-category weld S-N curve is represented in Figure 13 as an example.

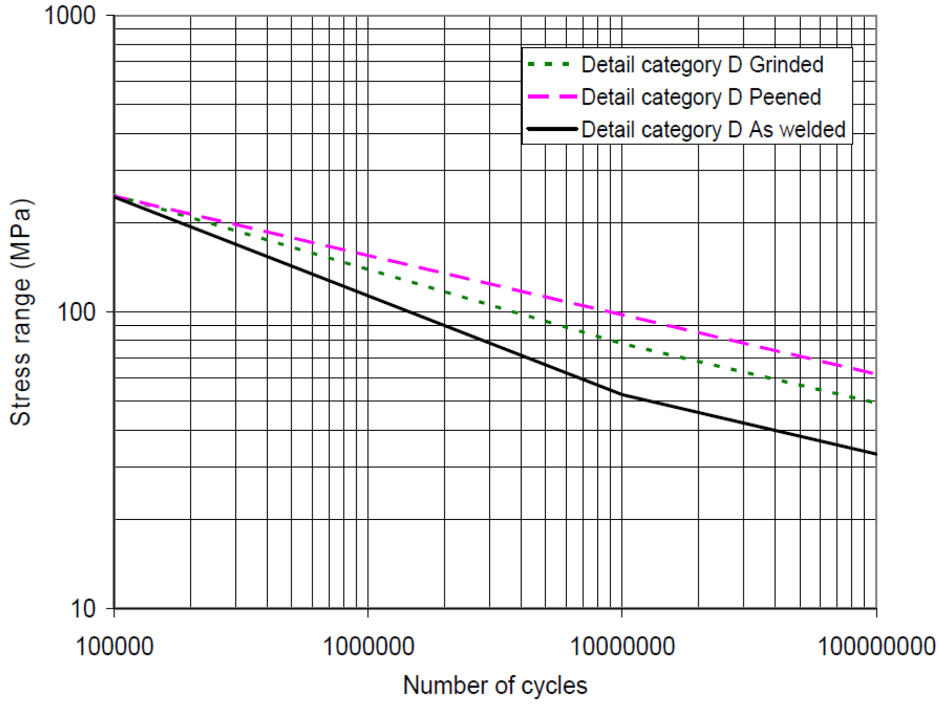


Figure 13. Example of DNV's D-category S-N curve for the as-welded and improved welds. [25]

Despite the fact that DNV gives improvement factors for the fatigue life for improved welds it also states that "*methods may not be recommended for general use at the design stage*" due to uncertainties regarding quality assurance. [15] [25] [23] In practise, obtained fatigue life improvement can be used only as a reserve and case-by-case type of approval. In practise, the classification society has a lot of room for consideration, how the method can be applied in practise at the design phase. In any case, improved S-N curves should always be used with caution. When selecting the corresponding S-N curve for the improved weld the location of the first failure crack initiation should be considered. In general the selected S-N curve depends on used NDT method as well. According to DNV, the weld improvement methods should not be applied for the low cycle fatigue condition. [25] [15]

The guidance between DNV and other classifications societies vary. Classification society Lloyd's Register (LR) gives very similar guidance regarding to fatigue strength improvement such DNV, notwithstanding the improvement factors given by LR are a bit smaller. [41] Classification society American Bureau of Shipping (ABS) has much limited guidance regarding the fatigue strength improvement. [48] As it has been seen, the classification rules are changing very slowly and the most optimistic test result cannot be referred since it is required to stay on the conservative side. However, in some special cases the use of improved fatigue strength obtained by HSS and treatment methods may be approved. Based on the literature and proposals done for the IIW it can be expected that in the future more benefits can be obtained.

3 ANALYSIS PROCEDURE

In order to evaluate the potential of HSS in fatigue critical structures analysis methods are needed. Following procedure is created to execute the research; see Figure 14. First, critical structural details and their geometry related parameters as well as all investigated conditions are defined. Secondly, fatigue calculations are done and allowable stress ranges corresponding to the determined design fatigue life are solved by iterating fatigue damage under the defined fatigue life. Fatigue analysis is done based on the hot spot stress method and S-N curves obtained from the previous research results. For comparison, values given by the classification society DNV are used as well. The long term stress distribution is presented as a two-parameter Weibull distribution. Finally, obtained value is evaluated by Cost-Benefit analysis.

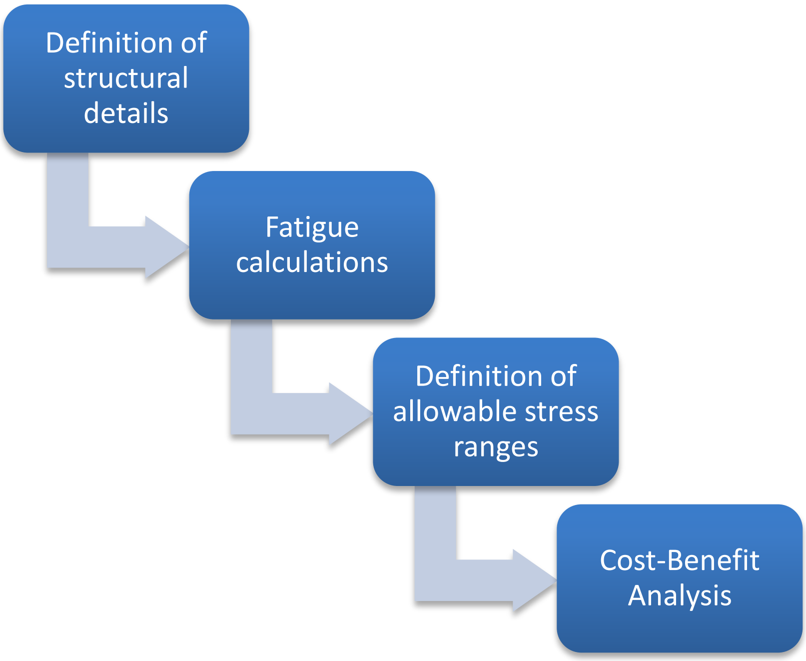


Figure 14. Procedure flow diagram.

3.1 Definition of structural details

The definition of structural details for the analysis is based on the findings from the state of art review, recommendations of classification society, review of several old FPSO projects and estimation where the potential of the HSS could be utilized most; to reduce production costs and to increase the allowable stress range at the hot spot locations that are challenging from the design point of view. For example classification society DNV provides a list of fatigue critical details of FPSO, to which refined fatigue analysis is recommended to be done. [42]

Details with different connection types and geometries are selected. FPSOs are often converted from the existing tankers. In conversion projects the potential of HSS could be well utilized in structural details that will be modified or added. Selected details are presenting structures where improvement of fatigue strength could be beneficial and post-weld treatment methods could be applicable. Design and parameters of used structural sections are fictional. However, they are corresponding to real life design of FPSOs and conversion projects. They may not present the most typical geometries but highly fatigue optimized design.

Major benefit can be obtained when the number of certain detail type in the hull structure is large. Therefore double bottom longitudinal stiffener support with the hot spot at the stiffener flange at the weld toe ahead of the bracket nose is excellent detail to analyse economic benefits. In order to analyse benefits, the geometry of some selected structural designs are redesigned. The redesigns have been done to simplify the geometry and production while maintain similar stress range by weld treatment and increased yield strength of the base material. Geometry can be simplified while keeping the allowable stress range same if fatigue strength improvement obtained by HSS and post-weld treatment is high enough. Geometries and relevant parameters of determined structural details are presented in following chapters.

3.2 Fatigue calculations

Damage accumulation can be calculated based on the equation of Palmgren-Miner rule (3) which can be written:

$$D = \sum_{i=1}^{k} \frac{Nf(s)ds}{C/S_i^m} = N \int_0^\infty \frac{1}{C} S_i^m f(s) ds \tag{4}$$

where *D* is accumulated damage, $f(s)$ represents long term stress distribution, *C* and *m* are S-N fatigue parameters, *S* is stress range and *N* is total number of cycles.

Long term distribution of stresses is represented by a two-parameter Weibull distribution:

$$f(s) = \frac{h}{q}\left(\frac{S}{q}\right)^{h-1} e^{-\left(\frac{S}{q}\right)^{h}} ds \tag{5}$$

where q is Weibull scale parameter and h is Weibull shape parameter. DNV gives an equation for Weibull scale factor q:

$$q = \frac{\Delta\sigma}{(\ln n_0)^{1/h}} \tag{6}$$

where $\Delta\sigma$ is the stress range at probability level:

$$Q = \frac{1}{n_0} \tag{7}$$

and n_0 is the number of cycles over the time period for the stress range $\Delta\sigma_0$. In the fatigue analysis convention is to use daily level stress response with $n_0 = 10^4$.

Weibull shape parameters are defined based on the classification rules by DNV and empirical factors found from the literature. It can be noted that the calculated fatigue damage is very sensitive for the value of shape factor h.

Nominal stresses have to be transferred to hot spot stresses by using equation (1) before entering to the S-N curves. Hot spot stress concentration factors given by DNV are used. They are based on the finite element analysis of the actual geometries.

Increasing the plate thicknesses reduces the fatigue capacity of welded joints. In classification rules this is typically taken into account by an additional factor on stresses. Thickness correction factor is calculated for the plate where cracking is expected:

$$thickness\ correction\ factor = \left(\frac{t}{t_{ref}}\right)^{b} \tag{8}$$

where t is the material thickness, t_{ref} is reference material thickness and b is thickness exponent. In DNV fatigue rules t_{ref} = 25 mm for plated joints. DNV has determined values for thickness exponents b depending on the design S-N curve that used.

Finally, the damage can be calculated based on two slope S-N curve by following equation:

$$D = \frac{N}{A} S^{m_1} (\ln N_T)^{\frac{-m_1}{h}} \Gamma\left(1 + \frac{m_1}{h}; \left(\frac{S_1}{q}\right)^h\right) + \frac{N}{C} S^{m_2} (\ln N_T)^{\frac{-m_2}{h}} \gamma\left(1 + \frac{m_2}{h}; \left(\frac{S_1}{q}\right)^h\right) \quad (9)$$

where Γ is upper incomplete Gamma function, γ is lower incomplete Gamma function and S_1 is stress range where change of S-N curve slope occurs.

Four different conditions are investigated, see Table 2. First condition is referring to as-welded condition and current classification rules, without any fatigue strength improvement methods applied. It is defining a base level of this analysis. Since hot spot stress approach is applied, D-curve for all details is to be used based on the Section 4.3.5 in DNV RP-C203; see S-N data in the Appendix B. [25] At the second condition *increase in fatigue life* –factors for weld improvement methods, given by DNV are used, see Table 1. It is stated in the classification rules that the maximum S-N class that can be obtained by weld improvements is C1 or C. Therefore the limit stage for the improvement which corresponds to C-curve is calculated at the 3rd condition. Finally, 4th condition is referred to S-N data from the literature [33], see Figure 11. The data from the literature can be understood as a best case scenario. The used S-N data from the literature is based on the experimental studies and values give significantly higher fatigue life than current design rules by classification societies. Calculated S-N fatigue factors (one slope) for the literature condition are presented in Table 3. Three different steel yield strengths in each case are investigated; 235 MPa Normal Strength Steel, 355 MPa and 550 MPa High Strength Steels.

Table 2. Conditions that used in the fatigue analysis.

No.	Condition
1	As-welded (DNV)
2	Improvement of fatigue life by fabrication (DNV)
3	C-curve (DNV)
4	S-N data given in literature

Table 3. Calculated S-N fatigue factors for FAT classes given in literature.

Steel yield strength [MPa]	Slope m	Log a
< 355	5	17,03
355 ≤ Δσ < 550	5	17,32
550 ≤	5	17,58

Mechanical peening treatment which is known as a residual stress method is applied in the analysis. Selection of this method is based on the knowledge that it is having a great potential for ship and offshore structure applications, as well as significant fatigue strength improvement capacity observed at the state of art review. Peening method can be used in all positions, as long as there is good access to the weld seam.

Classification society DNV gives improvement factor for hammer peening treated weld joints which is analysed in 2^{nd} condition whereas literature S-N data in 4^{th} condition is based on the High Frequency Mechanical Impact (HFMI) method. HMFI tool is advanced version of hammer peening tool by using higher impact frequency. However, the principle of the weld improvement is the same.

3.3 Definition of allowable stress ranges

As a result of fatigue analysis typically fatigue damage or fatigue life is achieved. However, since the economic benefits for different geometries are investigated it is more reasonable to solve allowable stress range instead of the fatigue life. Therefore the allowable stress range is solved by iterating the fatigue damage $D \rightarrow 1$ under the determined design life. Design life time of 25 years is determined. Therefore, total number of cycles during the life time 1.25×10^8 is used. It is corresponding to average period of 6.3 seconds. [25] Iteration is done separately for each detail under each condition investigated.

The increase of allowable stress range is achieved by the HSS and different weld improvement methods. Therefore the as-welded joints are analysed comparable by assuming that the design is optimized for the same fatigue design life. This means that for improved fatigue capacity welds the allowable stress range will be higher than for the as-welded joint.

3.4 Cost-Benefit Analysis

Typically costs and benefits can be analysed by so-called CBA (Cost-Benefit Analysis). The aim of the CBA is to numerically compare benefits and cost, measured in money. First, all remarkable variables related to additional costs and savings are determined, see Table 4 and 5. The maximum net benefit is obtained in the case when variables listed as additional cost are having minimum value and the variables listed as saving are having greatest value. In addition, there are fixed cost such as equipment investments and training.

Table 4. Cost type variables related to post-weld treatment.

Type of additional cost	Unit to measure
Treatment work	Man-hour
Quality control	Man-hour
HSS steel (compared to NSS)	€

Table 5. Benefit type variables related to post-weld treatment.

Type of saving	Unit to measure
Production time (welding)	Man-hour
Material saved	Ton

Analysis of obtained net benefits based on the current classification practise is complex. Case-by-case type of approval principle and recommendation not to apply the method in general at the design stage (by classification society) means, that the method can be used only as a "backup-tool" to locally improve fatigue strength of single hot spot. Typically at the point of time when the fatigue life of the structural details are analysed, the design is already quite far and most of main geometries are locked. Hence, any major modifications are not possible to be done, or they may cause very high costs and delay the delivery of the vessel in the worst case.

However, in favourable scenario high strength steels combined with post-weld treatment could be used locally for larger amount of structural details, and as a part of normal fatigue design practise. Hence, benefits are analysed under the scenario that case-by-case type of approval is not applied and the method would be considered as general practise at the design stage. Under that scenario, benefiting from the HSS with the weld treatment can be estimated by following equation:

$$B_T = (S_T - C_T) \times N_D \tag{10}$$

Where B_T is the net benefit, S_T is total savings, C_T is total amount of additional costs and N_D is the number of certain details. Based on the Table 5 the equation of total savings S_T can be written:

$$S_T = \sum(T_p \times K_T) + \sum(W_m \times K_m) \tag{11}$$

Where T_p is saved time in production, K_T is man-hour cost, W_m is weight of the saved steel material and K_m is the material price per ton. Based on the Table 4 the equation of total addition costs can be written:

$$C_T = \sum((T_t + T_{PT}) \times K_T) + \sum(T_q \times K_T) + \sum(W_{HSS} \times K_{HSS}) \quad (12)$$

Where T_t is time needed for the treatment work, T_{PT} is the time needed for work preparation and transit from hot spot to another, T_q is the time needed for the quality control, W_{HSS} is the weight of the HSS material and K_{HSS} is the addition material cost due to use of high strength steel instead of nominal strength steel

The exact values for undefined production yard cannot be determined. The values vary for example depending on the production place, time, material quality, labour, used methods and tools. Hence, minimum and maximum values for each variable are estimated and average value is calculated accordingly.

4 STRUCTURAL DETAILS FOR HSS UTILIZATION

Several fatigue critical structural details can be found from the hull structure of FPSO. Following structural details have been selected for this analysis, see Table 6. They are found to be fatigue critical based on the experience from practice and literature; see Figure 15 how they are located in the FPSO hull. The design of these details is based on classification data from DNV, improved design by finite element analysis and findings in the state of art review related to fatigue behaviour of FPSO.

Table 6. Selected structural details for the fatigue analysis.

Detail 1	Flexible topside support
Detail 2	Helideck support structure (Gusset connection)
Detail 3	Fatigue optimized stiffener support
Detail 4	Typical stiffener support
Detail 5	Simplified stiffener support

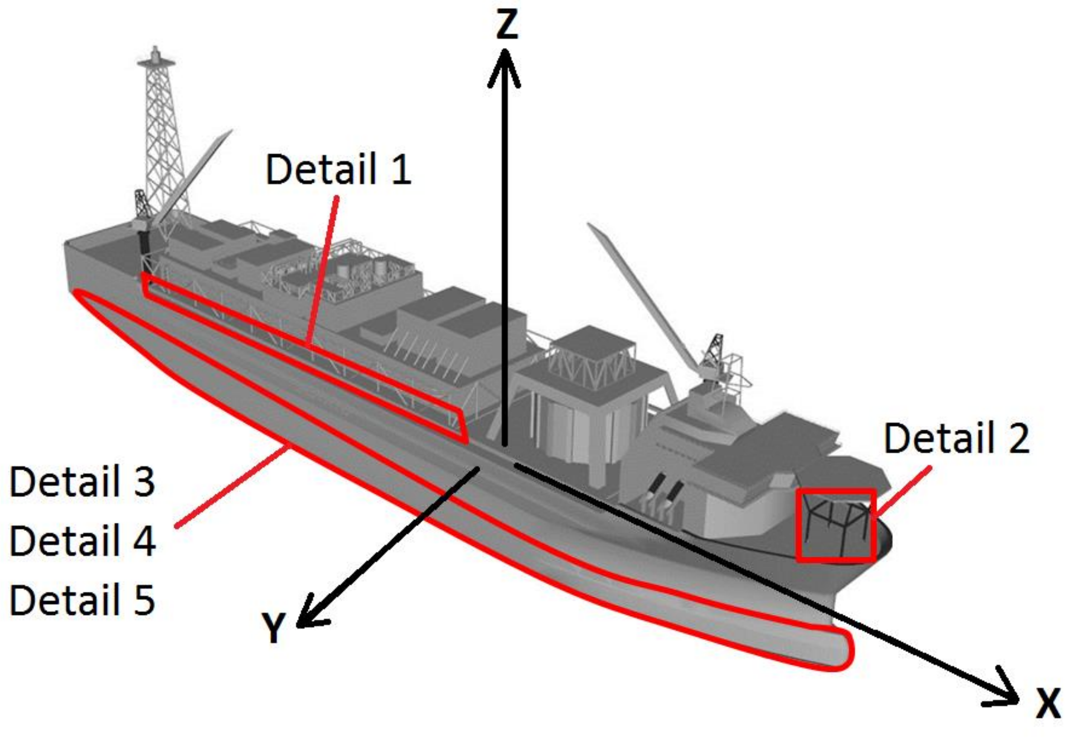


Figure 15. Applied coordinate system and location of the analysed details marked with the red colour.

For each detail, hot spot locations and a free body diagram in fatigue point of view with relevant directions are presented. Coordinate system applied is presented in Figure 15.

As a summary; 5 details x 4 conditions x 3 steel yield strengths = 60 cases are calculated in total. First, each detail is presented. Secondly fatigue analysis results are presented and finally, the meaning of the results is evaluated by cost-benefit analysis in Chapter 6.

4.1 Detail 1: Flexible topside support

Topside supports are used to transmit heavy weights of topside modules to hull structures. Various topside support designs exist. They vary in terms of type and number of supports used. The structural geometry used in this thesis is represented in Figure 16 in 3D and in Figure 17 in 2D view. Topside supports are arranged according to primary structural members of the hull. Loads at the interface of hull and topside supports are depending on the weight of the module as well as hull motions, accelerations and flexibility of the topside support. Topside structures are exposed to hull girder deflections as a result of hull girder global vertical and horizontal bending. Bending moment and the module weights are inducing high stresses to supports and interface between support and deck plate. Wave axial force and dynamic module inertia loads are acting on the structure as well.

As a result of hull deformations, all topside supports cannot be rigid. Therefore, at the end of the topside module flexible supports are used to separate topside structures from the hull deformations. The flexible support is implemented by unstiffened section on the web plate of the support. Flexibility reduces effect of stresses at the interface of deck plate and topside structures. Insert plates between the support and deck plate can be used as well.

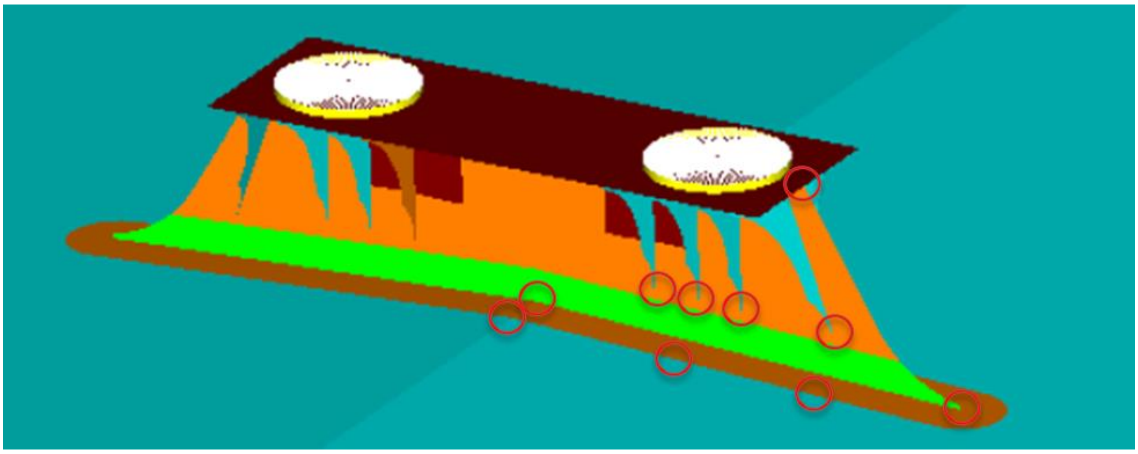


Figure 16. Flexible topside support 3D view. Topside support is welded to the insert plate on the deck. SB side hot spot locations presented with the red circles.

A thin web plate is used due to flexibility. However, it is ideal from the fatigue point of view. Thickness of the web plate cannot be increased significantly. Neither the geometry can be changed into more fatigue optimized, if completely other type of design is not applied. Therefore this detail is investigated in order to increase the maximum allowable stress range at the hot spot location. If stress range could be cost-efficiently increased by post-weld treatment it would be very beneficial for this type of detail.

Hot spots occur at the support web plate, at the deck plate on top of the longitudinals and at the connection of the insert plate and deck plate. Investigated hot spot occurs at the Centre Line (CL) at the interface of the deck plate and topside support web plate; see Figure 17.

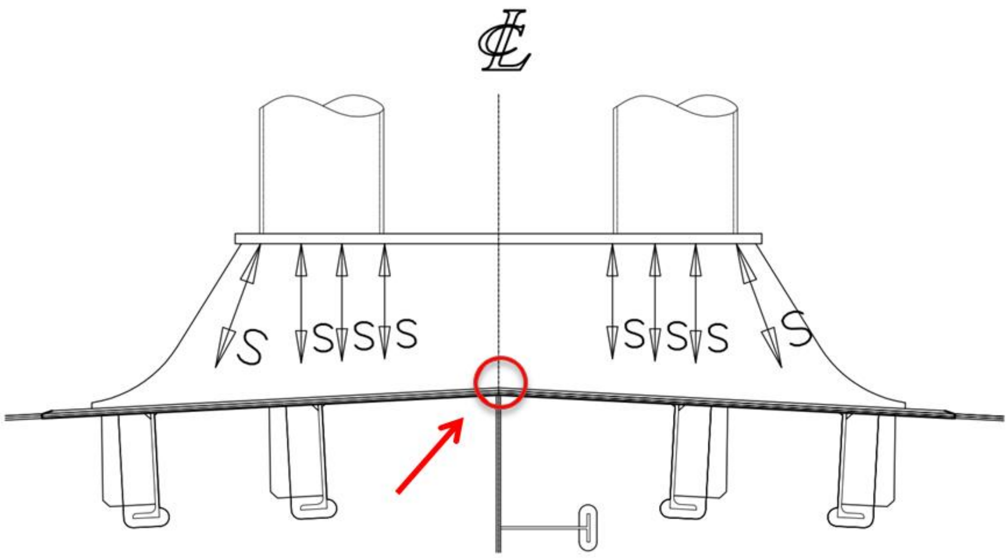


Figure 17. Flexible topside support at CL. Below the deck plate bulkhead is located at CL. Analysed hot spot location is presented with the red arrow.

Topside support is located on the transversal web frame which supports heavy topside module loads. At the CL, longitudinal bulkhead below the deck plate results hot spot to the web plate of support; see free body diagram of Detail 1 in Figure 18. As a result of bulkhead and web frame located below, the surface of the deck plate at the CL is a hard point. Therefore nominal stress is not determined for this detail. Only the allowable hot spot stress range is calculated.

Plate thickness of the flexible web is t = 30 mm. Plate is full penetration welded on the relatively thick insert plate.

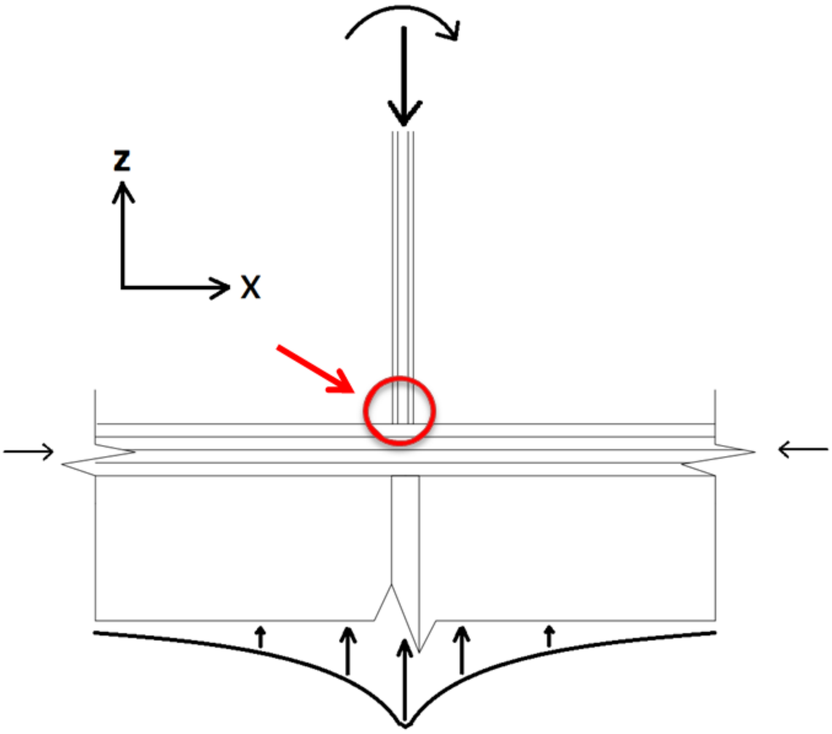


Figure 18. Free body diagram of Detail 1 (transversal cross section view from CL). Flexible topside support connection to the insert plate. Flexibility is implemented by unstiffened section on the web plate of the support. Analysed hot spot location presented wit

DNV classifies this connection type for category F (t > 25 mm), ref. DNV-RP-C203; see Appendix A. For F category connection DNV has determined the stress concentration factor 1.27; see Appendix B. Accordingly, SCF 1.27 is applied for hot spot located at the interface of topside support web plate and deck plate. D-curve (for hot spot approach) in air is used; see S-N data in the Appendix B.

Long term Weibull shape factor for the topside support welded on the main deck is calculated by equation given by DNV:

$$h_0 = 2{,}21 - 0{,}54 \times logL \tag{13}$$

where L = 285 m is the length of the ship. Equation (13) gives a result of h = 0.82. Thickness correction factors of 1.04 for the D-curve and 1.03 for the C-curve are calculated based on the equation (8).

4.2 Detail 2: Helideck support structure

Helideck platforms are needed in all offshore structures to enable fast transport of people and small equipment. Especially in emergency situations when vessel has to be evacuated rapidly. In FPSO, the area below helideck is typically effectively used for other deck outfitting components. Therefore supporting helideck structure is challenging due to lack of free space on the deck area. As a result of safety and short connection to accommodation spaces, typically it is located to either fore or aft part of the vessel. Vessels motions and accelerations are greatest there, which is not an ideal location in fatigue and strength point of view. As a result of accelerations and motions, inertia loads are acting in the helideck structure. However, the global vertical bending moment is smaller in fore and aft than amidship. In fatigue point of view sway motion is the most significant; see free body diagram in Figure 20. Several other loads, such as wind and dead load and impact load of the helicopter are imposed to helideck support structure as well. However, in terms of fatigue they are not significant. In fatigue point of view inertia loads are governing and other varying loads are typically ignored. Sea pressures are not considered due to high position of the helideck support structure.

Typical helideck support structure is represented in Figure 19. It consists of tubular pillars that are building a cross-supported structure that is holding up the helideck. Welded tubular and Gusseted connections are used.

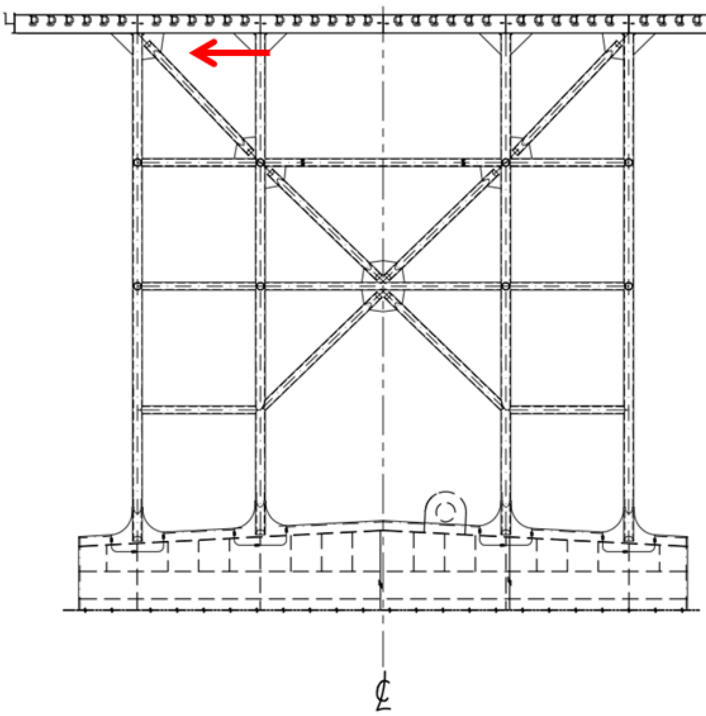


Figure 19. Transversal view of helideck platform and support structure. Selected Gusset connection detail presented with the red arrow.

The helideck support structure is high and relatively light structure. Additional steel (weight) for the upper parts is not preferred. Neither the geometry can be significantly improved from the fatigue point of view. Therefore, if maximum allowable stress range at the hot spot locations could be increased by weld treatment at the fatigue critical locations it would be beneficial. Additional cost by post-weld treatment would be low for this detail type as the amount of treated weld meters at the connection is low. Therefore this detail is investigated in order to benefit from the allowable stress range increase.

Gusset plates are used as a connection method for cross-supported structures at the spots where several members join together. Tubular pillar is welded to the Gusset plate. Hot spot locations are presented with the red circles; see Figure 20. The investigated hot spot is presented with the red arrow. Pillar has dimensions of Ø250 x 16 mm and the Gusset plate has material thickness of t = 16 mm. Full penetration welds are used as a connection type.

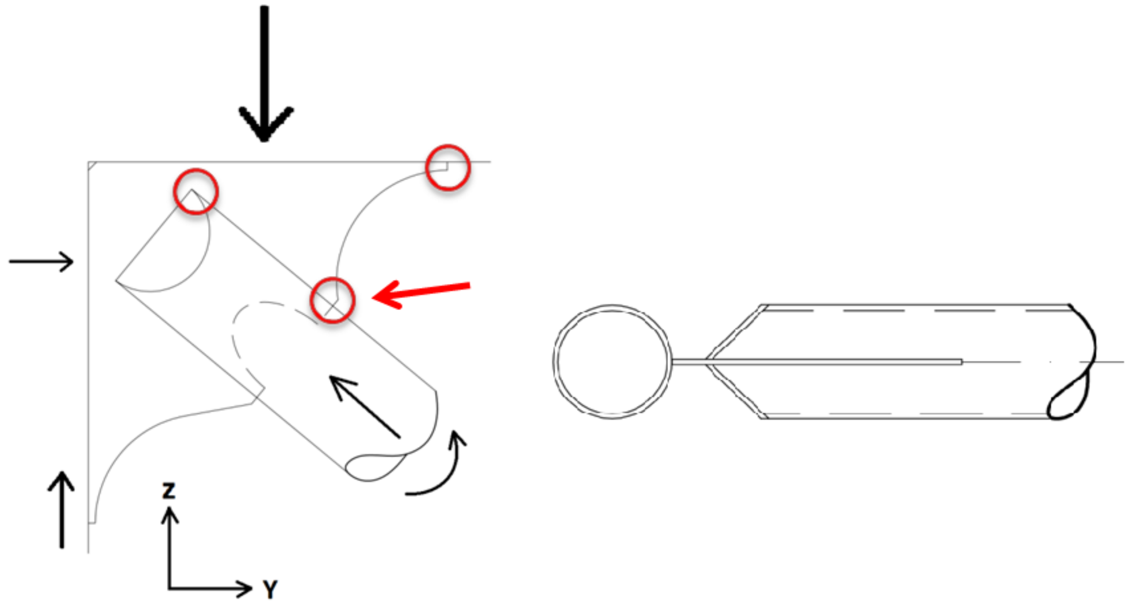


Figure 20. Free body diagram of Detail 2 at left side and connection type presented at right side; joint with a gusset plate (favourable geometry). Hot spot locations presented for the one side (symmetrical) with the red circles. Investigated hot spot presented.

DNV gives the stress concentration factor 2.3 with favourable geometry of Gusset plate and 3.0 with simple shape of gusset plate; see Appendix C. The favourable geometry gusset plate is applied for this detail. Therefore SCF 2.3 is applied. D-curve (in air) is to be used; see S-N data in the Appendix B.

For this detail, Weibull shape factor h = 0.85 is assumed. The plate thickness is less than 25 mm. Therefore thickness correction factor is 1.0

4.3 Detail 3: Fatigue optimized stiffener support

Double bottom section consists of inner bottom plate, bottom shell plate, floors, longitudinal stiffeners and stiffener supports; see Figure 21. Several loads have to be considered; Global hull girder loads such as vertical and horizontal bending moments and axial forces. In addition internal and external loads such as external pressures and tank pressure are acting in double bottom structures as well. Loads are inducing bending moments and axial forces to the longitudinal stiffeners; see free body diagram of the Detail 3 in Figure 22. As a result, hot spots occur at the stiffener flanges at the weld toe ahead of the bracket nose.

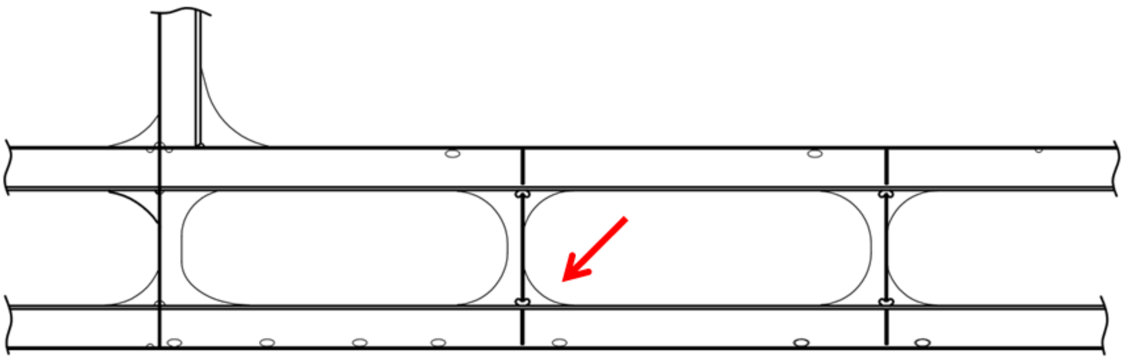


Figure 21. Side view section of double bottom structure. Selected bracket presented with the red arrow.

In terms of fatigue, challenging locations in double bottom section are stiffener supports with hot spots at the stiffener flanges at the weld toe ahead of the bracket nose. Brackets are used at the corners where otherwise would be high stress concentration. Stress flow is smoother through the bracket and it is significantly reducing the stress concentration at the corner. However, high stresses occur at the bracket toes and it has been recognized as critical from fatigue point of view. Hot spots are presented with the red circles; see Figure 22. Investigated hot spot is presented with the red arrow.

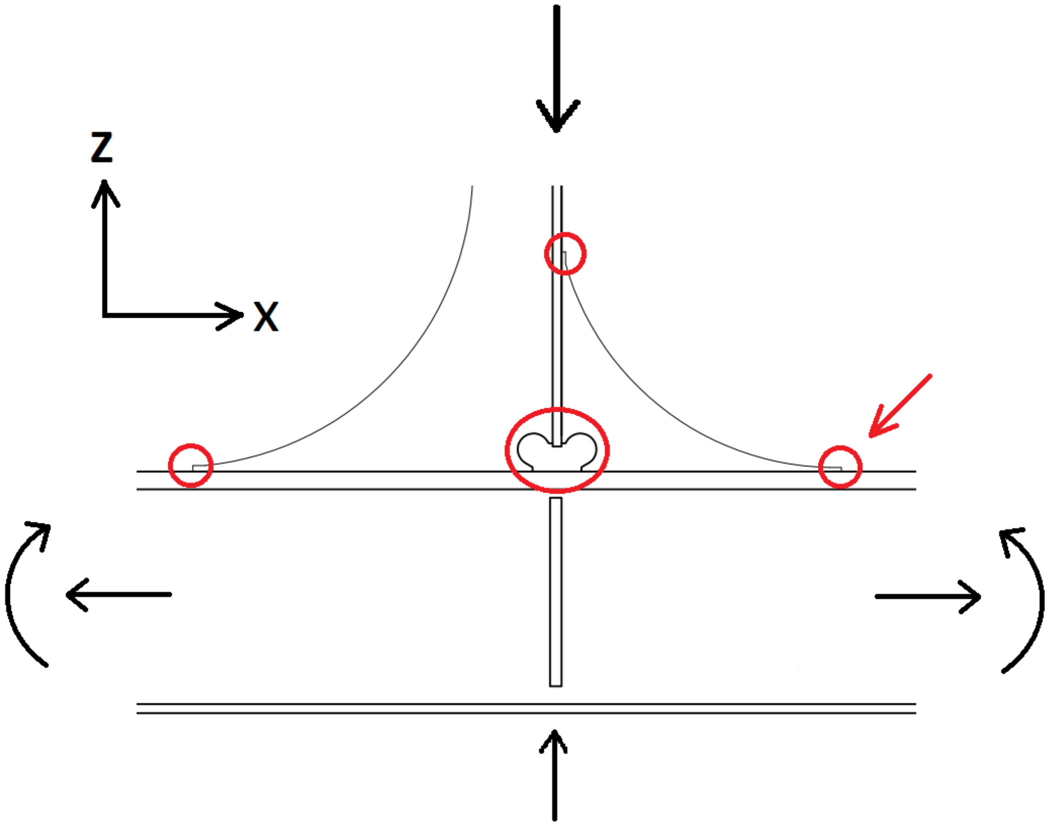


Figure 22. Free body diagram of Detail 3. Hot spot locations presented with the red circles. Analysed hot spot location presented with the red arrow.

This detail presents fatigue optimized geometry that may be used when high fatigue strength is needed. However, the geometry is complex and costly to produce since large number of similar details exists at the double bottom structure. This detail is investigated in order to simplify the structural geometry and evaluate the obtained benefits whereas similar allowable stress range should be kept. By weld treatment and increase of the yield strength of base material the geometry of the detail may be simplified while the similar maximum allowable stress range is remained.

Material thickness of the bracket is t_b = 22 mm, radius R = 900 mm, bracket nose height is 10 mm and the angle of bracket nose is parallel with the stiffener. As the bracket nose height is only 10 mm it has to be first welded with the greater nose height, and after welding grinded to the 10 mm height. A web of longitudinal stiffener has dimensions of 12 x 575 mm and flange 22 x 150 mm; see Figure 23. Bottom plate thickness is t_p = 22mm. Full penetration weld is used as a connection type between bracket and longitudinal stiffener.

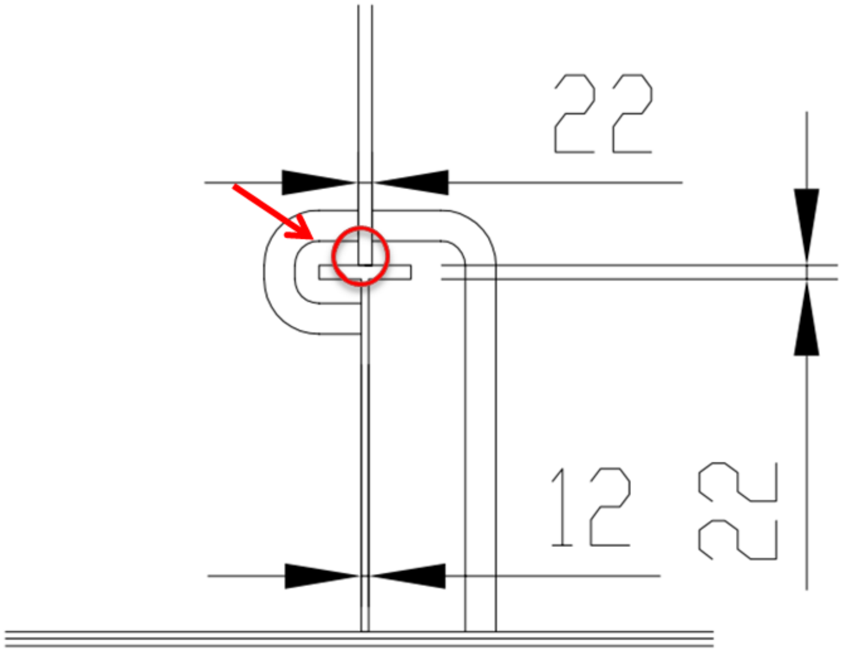


Figure 23. Cross section view from the longitudinal stiffener support bracket. Analysed hot spot location presented with the red arrow.

For soft nose bracket (R = 900) toe the stress concentration factor of $K_{g,axial} = K_{g,bending}$ = 1.22 is determined based on the DNV rules; see Appendix D, geometry B-3.4. Accordingly, SCF 1.22 is applied for this detail. D-curve (seawater + cathodic protection) is used; see S-N data in the Appendix B.

For the bottom longitudinal Weibull shape factor is calculated by equation:

$$h = h_0 - 0,005 \times T_{act} \tag{14}$$

where h_0 is expressing the equation (13) and T_{act} is the actual draught of the vessel. Value of T_{act} = 12 m is applied. Therefore equation (14) gives a result of h = 0.82. The plate thickness is less than 25 mm. Therefore thickness correction factor is 1.0

4.4 Detail 4: Typical stiffener support

This detail is analysed in order to investigate benefits related to simplified geometry obtained by the post-weld treatment. Detail 4 presents the similar double bottom stiffener support with hot spots at the stiffener flanges at the weld toe ahead of the bracket nose as the previous, Detail 3. The loading condition is considered similar as well. However, Detail 3 represents strongly fatigue optimized geometry whereas Detail 4 presents more common stiffener support geometry. Compared to the previous detail, around half as much welding and grinding are needed as well as less steel material. Hot spots are presented with the red circles and investigated hot spot is marked with the red arrow; see Figure 24.

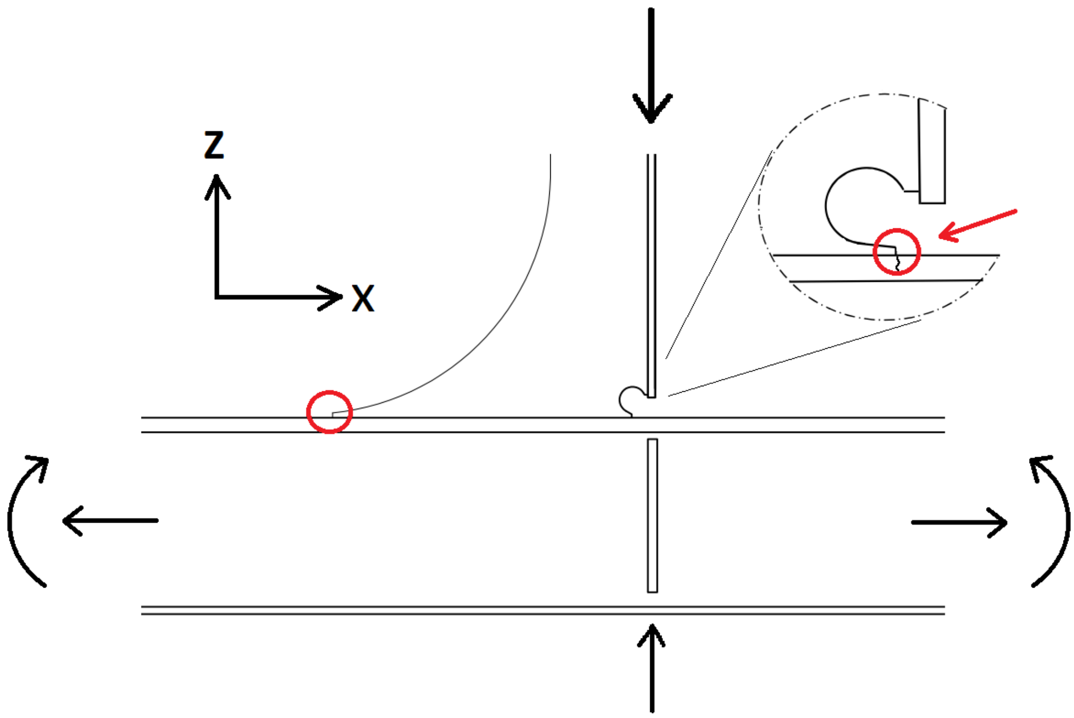


Figure 24. Free body diagram of Detail 4. Hot spot locations are presented with the red circles. Analysed hot spot location is presented with the red arrow.

Radius of the bracket is R = 700 mm and plate thickness t_b = 22 mm. For the soft heel scallop radius greater than 30 mm should be used. Same dimensions for the longitudinal stiffener are expected. Values of $K_{g,axial}$ = 1.18 and $K_{g,bending}$ = 1.24 for the soft toe bracket nose and $K_{g,axial}$ = 1.24 and $K_{g,bending}$ = 1.53 are determiner for this detail based on the DNV classification rules, see Appendix D, geometry B-3.3. Accordingly, SCF 1.53 for the scallop in bending loading can be seen giving smaller (limiting) value for the allowable nominal stress range and therefore it is applied for this detail. Otherwise, same parameters are used than in Detail 3.

Cracking on the stiffener flange at the weld toe ahead of the scallop nose as first likely failure mode in scallop is expected. Analysis of cracking in the base material is excluded in scope of this thesis. However, high stresses may occur at the base material and when fatigue strength of the weld toe is improved it may become critical.

4.5 Detail 5: Simplified stiffened support

Such as previous detail, this detail is also analysed in order to investigate benefits related to simplified geometry obtained by the post-weld treatment and HSS. Detail 5 presents the similar double bottom stiffener support with hot spots at the stiffener flanges at the weld toe than two previous. The loading condition is considered similar than previous stiffener support details. However, Detail 3 represents strongly fatigue optimized geometry whereas simple geometry Detail 5 is optimized in terms of costs; see Figure 25. Significantly less material and welding is needed. Hot spots are presented with the red circles and investigated hot spot is marked with the red arrow.

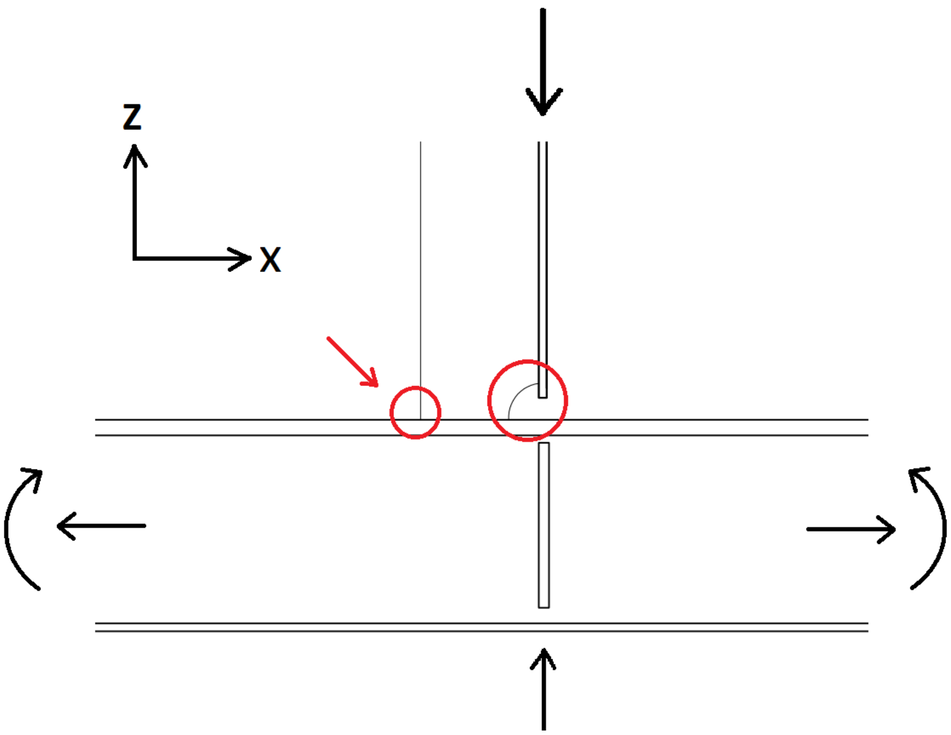


Figure 25. Free body diagram of Detail 5. Hot spot locations are presented with the red circles. Analysed hot spot location is presented with the red arrow.

Values of $K_{g,axial}$ = 1.40 and $K_{g,bending}$ = 1.60 for the both hot spots presented are determined based on the DNV rules; see Appendix D, geometry B-2.1. Accordingly, SCF 1.60 is applied for this detail. Otherwise, same parameters are used than in Detail 3 are used.

5 FATIGUE STRENGTH COMPARISON

Fatigue strength comparison is executed by the procedure described in the Chapter 3. Fatigue calculation is done based on the hot spot stress S-N data. Long term distribution of stresses is expressed by Weibull distribution. Instead of fatigue life, the maximum allowable stress range is solved for each detail in four different conditions (As-welded, DNV improved, DNV C-curve and Literature S-N data) and three steel strengths (235 MPa, 355 MPa and 550 MPa). Previously determined stress concentration factors, Weibull shape factors and material thicknesses are used as input values; see Table 7.

Table 7. Input values for the fatigue calculations. Thickness is given for material which through the potential crack will grow.

Detail	SCF	Weibull shape factor *h*	Thickness [mm]
1	1.27	0.88	30
2	2.30	0.85	16
3	1.22	0.82	22
4	1.53	0.82	22
5	1.60	0.82	22

Following allowable hot spot stress ranges have been achieved from the fatigue analysis under the determined design life time of 25 years (corresponding to 1.25 x 10^8 load cycles); see Figures 26 and 27. Exact values are presented in the Appendix E.

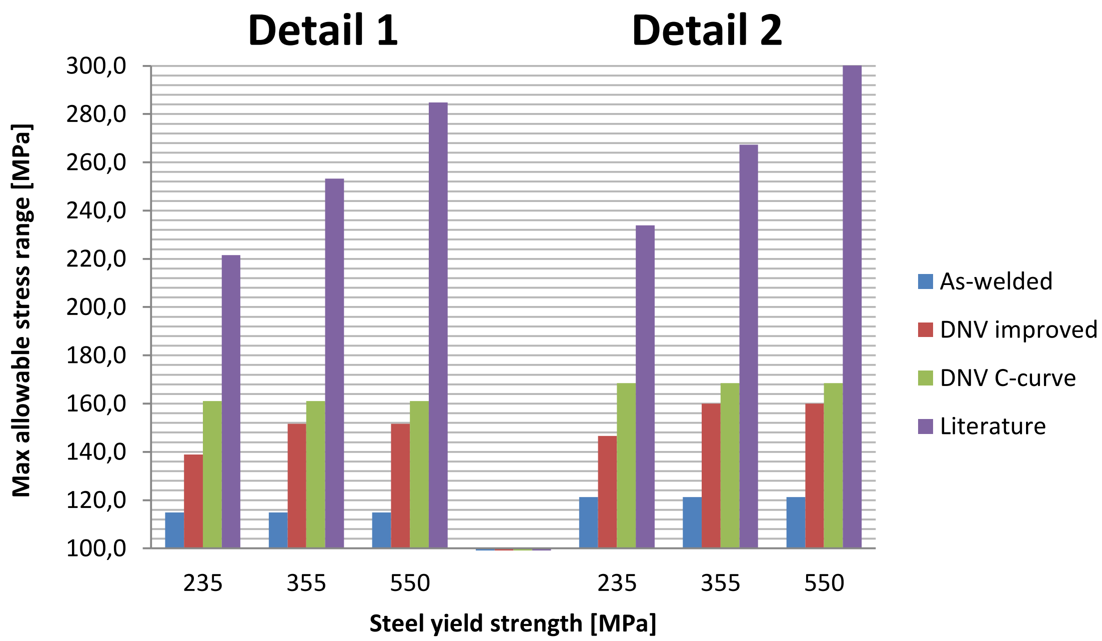


Figure 26. Maximum allowable hot spot stress ranges for Detail 1 (left side) and Detail 2 (right side).

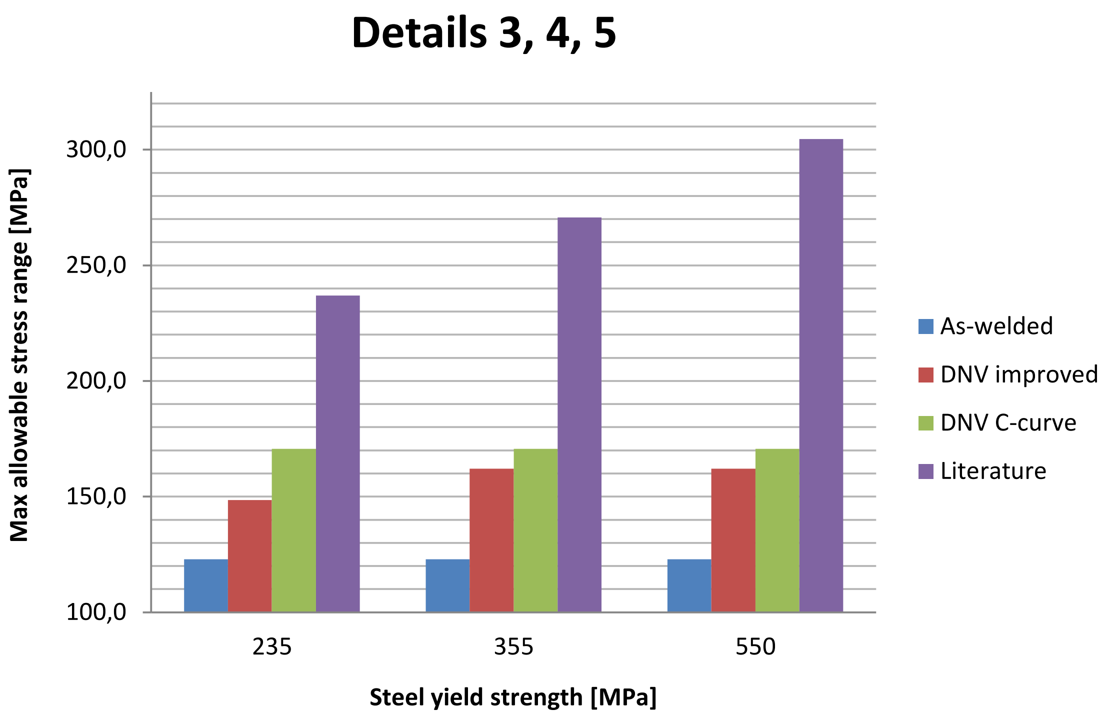


Figure 27. Maximum allowable hot spot stress ranges for Detail 3, 4 and 5. Hot spot stress range is equal for Details 3-5.

Since Details 3, 4 and 5 are presenting similar structural detail the hot spot stresses at the stiffener flange are equal. In all cases it can be seen that maximum allowable stress range is significantly increased as a result of weld treatment and increased yield strength of the base material. The increase of the allowable hot spot stress range based on the DNVs fatigue life improvement factors is level of 25-40 MPa whereas improvement based on the literature S-N data is greater than 100 MPa in each case.

In some cases the increased stress range may even exceed the fatigue strength of the unwelded base material. However, in practise it is not realistic to use higher stress ranges than the unwelded base material can resist. Therefore the fatigue strength of the unwelded base material should be used as upper limit for improved fatigue strength of the welded connections.

Hot spot stress ranges have been transferred to nominal stress ranges by using relation between nominal stress and hot spot stress given in equation (1). For Detail 1 only hot spot stress ranges are calculated due to hard point. For Details 2-5 following allowable nominal stress ranges have been determined; see Figures 28 and 29. Exact values are presented in the Appendix F.

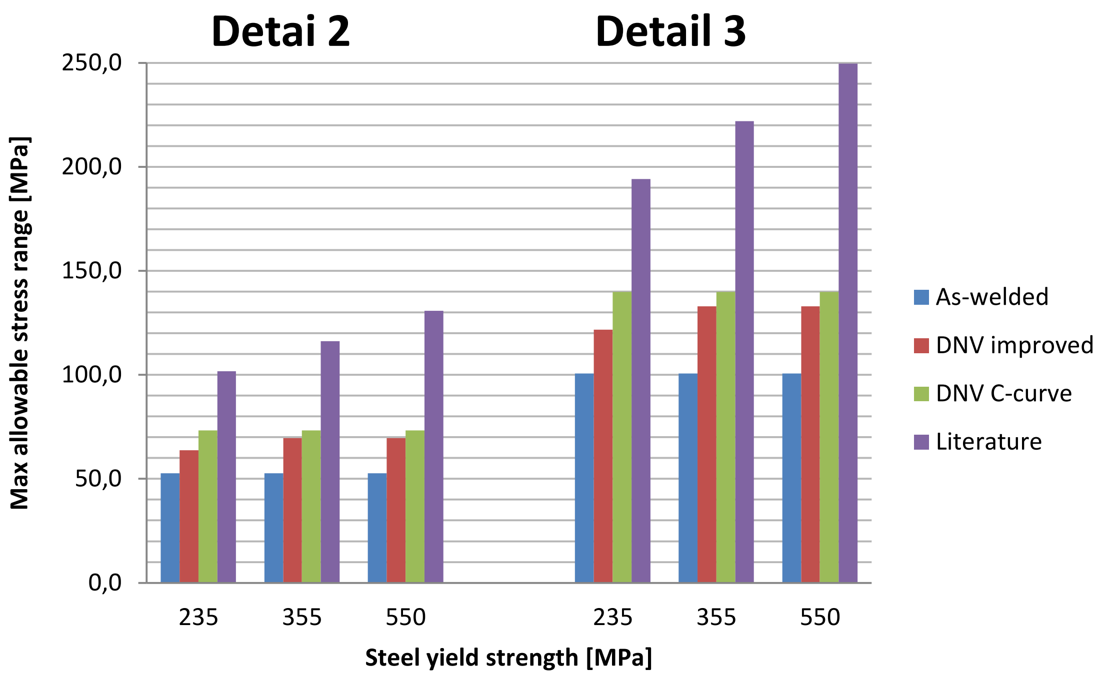


Figure 28. Maximum allowable nominal stress ranges for Detail 2 (left side) and Detail 3 (right side).

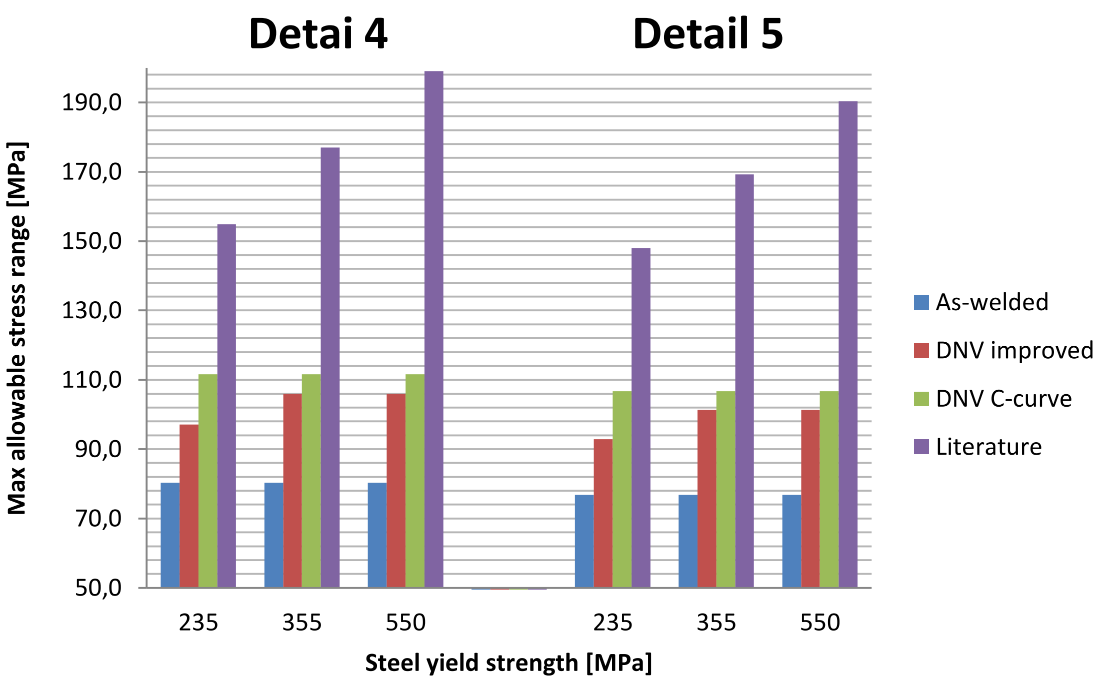


Figure 29. Maximum allowable nominal stress ranges for Detail 4 (left side) and Detail 5 (right side).

Stress ranges with DNV C-curve are calculated as they present the maximum value that can be obtained by weld treatment with the current classification rules by DNV. It can be seen that in each case the maximum allowable nominal stress range calculated with the C-curve is larger than value calculated with the improvement factors. It means that C-curve is not limiting the fatigue strength improvement obtained by DNV improved factors. Therefore the values calculated with the improvement factors are valid, and the C-curve values can be excluded from the further analysis.

Increase of the allowable nominal stress range for improved welds is compared to the as-welded base condition. When values are rounded to the nearest integer, equal result for each investigated detail has been obtained; see results in Table 8.

Table 8. Obtained increase of nominal stress range. As-welded condition is used as a base value (100%). Similar increase of the nominal stress range obtained for each detail.

Nominal stress [%] when D = 1; Fatigue life = 25 years			
Yield strength	As-welded	DNV improved	Literature
235	100 %	121 %	193 %
355	100 %	132 %	220 %
550	100 %	132 %	248 %

Significant increase in the nominal stress range is obtained by weld treatment. With the NSS base material the increase is more than 20 % and with HSS more than 30 % when DNV improvement factors are used. Results based on the literature S-N data present even greater increase of allowable normal stress range. With the NSS base material increase is almost 100 % and with HSS the increase is greater than 100 %.

Increase of the fatigue strength can be also investigated by examining the relation between calculated fatigue life and maximum allowable stress range. The relation is presented for Detail 3 (355 MPa steel); see Figure 30. It can be seen that the increase of the fatigue life in low stress ranges is extremely high. The fatigue life can be multiple times compared to as-welded condition. In high stress ranges the difference narrows. Charts for each investigated case can be found in the Appendix G.

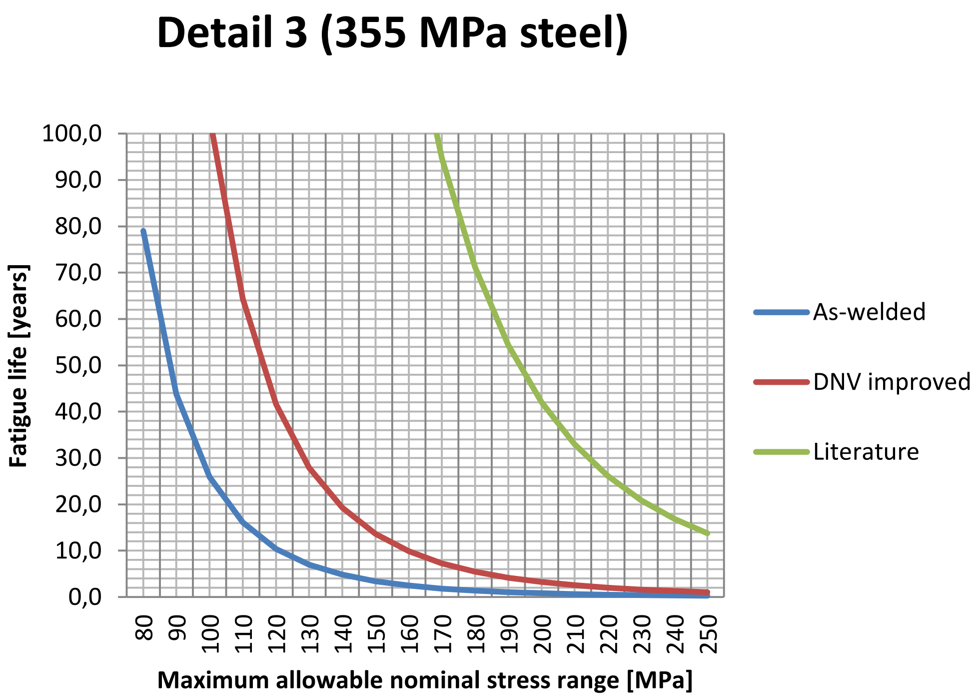


Figure 30. The relation between calculated fatigue life and maximum allowable stress range. Detail 3 with 355 MPa steel.

Evaluation of errors:

The fatigue analysis is based on the S-N data which are achieved by the fatigue tests made for the test specimens. S-N data given by DNV is associated with a 97.6 % probability of survival whereas S-N data for the improved weld from the literature with a 95 % probability of survival.

The fatigue life calculated by applied method is very sensitive for the value of Weibull shape factor *h*. However, it can be noted that the percentage nominal stress increase rate for the improved welds compared to the as-welded condition is nearly independent from the Weibull shape factor. Same applies for the value of SCF. Calculated hot spot stresses are highly depending on the value of SCF. If the investigated value would be the fatigue life, then more accurate values of SCFs would be beneficial. In order to obtain more accurate results Finite Element Analysis could be applied. However, considering the aim of this thesis, it does not bring any additional value.

6 COST-BENEFIT ANALYSIS

From the results of the fatigue analysis it can be already seen that the increase of the allowable stress range, or fatigue life that can be obtained by HSS with post-weld treatment is significant. However, it does not directly present what are the benefits from economic point of view. Therefore, cost-benefit related issues are discussed in this Chapter.

The results achieved from the fatigue analysis indicate that the improvement of the fatigue strength is significant for all details investigated. Local fatigue related issues at the weld toe areas can be solved by post-weld treatment method with HSS base material, expecting the decent level of fatigue strength excluding the effect of improvement. It should be remembered that fatigue strength of the insufficient design cannot be improved by any post-weld treatment method.

Investments for the equipment and training are relatively low in long period. The price of high frequency peening tool for professional use is approximately 10 000 euros and training needed as low as 10 hours. In one hour 10-18 meters of weld can be treated by one tool and worker. [38] [39] [43] The number of treated weld meters is also low since the treatment is needed locally for the stress concentration areas. It means that only very few man-hours of additional work for the treatment process is needed. Therefore the use of post-weld treatment can be taken as cost-efficient method in all cases when it could be considered to apply under the current classification practise. However, due to case-by-case type of approval and limited “backup” type of use, CBA analysis is not done under the current practise.

In favourable scenario high strength steels combined with post-weld treatment could be used locally for larger amount of structural details, and as a part of normal fatigue design practise. Hence, benefits are analysed under the scenario that case-by-case type of approval is not applied and the method would be considered as general practise at the design stage.

Details 3, 4 and 5 are expressing the same structural detail, double bottom stiffener support. However, they all have different geometry. It has been found that the same stress range can be remained for simple geometry stiffener support if HSS base material with post-weld treatment is used; see Figure 31 and Table 9.

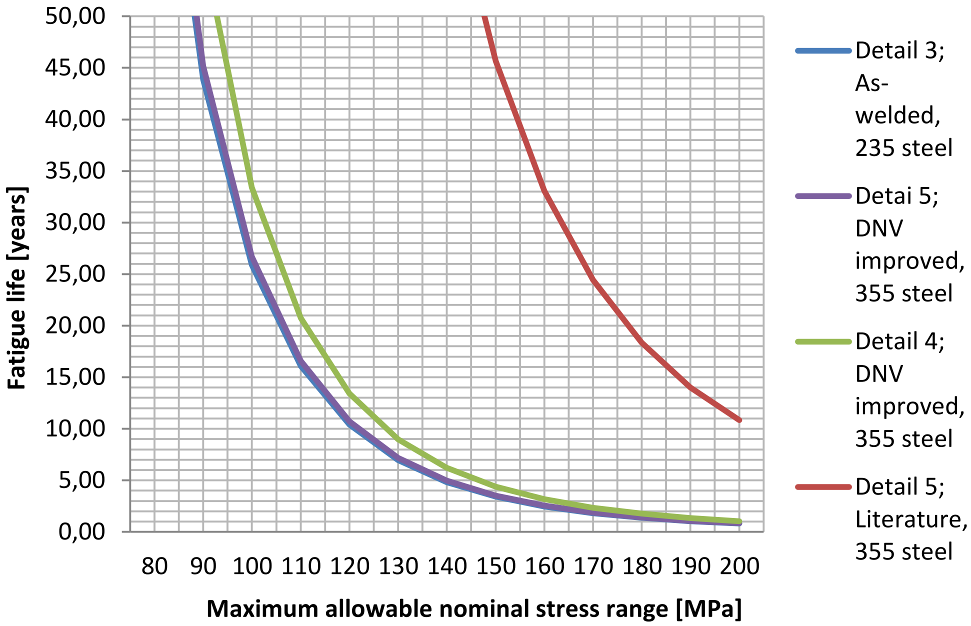
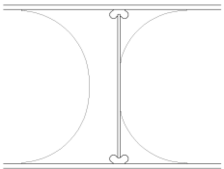
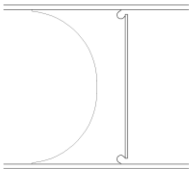
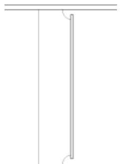
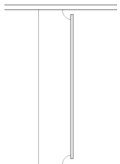


Figure 31. The relation between fatigue life and allowable nominal stress range compared for the different cases. First (blue) and second (purple) curves are having almost identical values.

For the Detail 3 as-welded condition the maximum allowable nominal stress range is 101 MPa in 25 year fatigue life. Similar stress range for the simple geometry Detail 4 and 5 can be obtained with 355 MPa HSS and peening method. By applying DNVs fatigue improved factors the calculated nominal stress range is 106 MPa for Detail 4 and 101 MPa for Detail 5. They both meet the calculated base level stress range of 101 MPa (Detail 3). Analysis based on the literature S-N data gives a stress range as high as 169 MPa for the Detail 5 which is significantly higher than the comparison level.

Table 9. Calculated maximum allowable nominal stress ranges for 25 year fatigue life. Steel weight and weld meters are presented for each detail. Detail 3 presents the base level.

	Detail 3	Detail 4	Detail 5	Detail 5
				
Steel yield strength	235 MPa	355 MPa	355 MPa	355 MPa
Condition	As-welded	DNV improved	DNV improved	Literature
Allowable stress range	101 MPa	106 MPa	101 MPa	169 MPa
Steel weight	173.3 kg	132.1 kg	63.5 kg	63.5 kg
Amount of weld seam	5.6 m	3.3 m	1.6 m	1.6 m

This indicates that although the highly fatigue optimized geometry is turned into simple cost optimized geometry the same fatigue strength can be remained. Simplified geometry in this context results savings in the production time and material as a result of less material and welding needed. However, small amount of additional work due to weld treatment is needed as well. Effects on the production cost can be analysed.

First, amount of steel material (stiffener support, t_b = 22 mm) and weld meters for analysed details are determined, see Table 9. Secondly, input values for the costs and man-hours needed for the changed parameters are to be determined. Based on the literature, following input values are determined [44] [45] [46] [47]; see Table 10. The breakdown of additional costs and savings can be found in the Appendix H.

Table 10. Input values for the cost analysis. Values are based on the literature.

Type	Min	Average	Max	Unit
Labor cost [47] [45] [48]	15	22,5	30	€/m-h
Steel price [46] [47]	550	650	750	€/ton
Welding speed [45]	6,6	7,8	9	h/m
Treatment speed [43] [39]	0,06	0,075	0,09	h/m

Labor cost presents the cost of one man-hour in the production. Steel price is estimated for the 235 MPa NSS. The higher price of the HSS steel used is taken into account by separate factor. Welding speed is estimated for the full penetration welding for 20-30 mm plate thicknesses and treatment speed for the HFMI-tool.

Based on the input values listed above, additional costs (presented in Table 4) and savings (presented in Table 5) for the redesigned geometries are estimated. Effect of the following variables is excluded from the CBA due to lack of information and relatively small impact; savings related to welding consumables, grinding, plate cutting, logistics and design work. Fixed costs such as investments and training are not included for the analysis either since the costs per one detail is relatively low.

From the cost- and saving-breakdown it is recognized that the welding is the most remarkable variable. Therefore, if significantly less weld meters are needed, the saving obtained will be significantly higher. The time needed for the actual treatment work is relatively very low. However, time for the preparation and transition from hot spot to other and from detail to other has to be taken into account since it has large impact for the total time spent for the treatment. In this analysis, a conservative value of one hour per structural detail is estimated for the preparation and transit. When all estimated cost type variables are subtracted from the savings, following net benefits compared to the design of Detail 3 are obtained, see Table 11.

Table 11. Calculated net benefits for the Detail 4 and 5 compared to the base design Detail 3.

Net benefit [€] per one detail

	Min	Average	Max	Unit
Detail 4	206	420	634	€
Detail 5	416	780	1144	€

Net benefit [M€] per 4000 details

	Min	Average	Max	Unit
Detail 4	0,8	1,7	2,5	M€
Detail 5	1,7	3,1	4,6	M€

In the upper table, net benefit is calculated per one detail whereas few thousands of this type of structural details may exist in one hull of FPSO. Therefore, the total net benefit for one hull is estimated by multiplying the benefits by 4000 details. Hence, the total net benefit is estimated to be in range of 1.7 - 4.6 million euros for Detail 5. Significant cost-saving and a large potential of the investigated method is recognized.

Calculated net benefit should not be taken as an exact value but for illustrative purposes. The aim is to present that a lot of potential exists. However, the minimum value of the obtained net benefit can be assumed to be on the conservative side whereas the maximum value may give over optimistic estimation. The obtained benefits highly differ depending on the applied structural details and production yard specific factors. The detail investigated in this thesis presents the type where the potential has recognised to be high. More accurate estimation could be done if variables for determined production yard as well as labor and material costs are known more accurately.

If the type of costs and savings are examined, it can be found that all additional cost as well as most of the benefits are governed by the shipyard; see Figure 32 and 33. In both investigated details the treatment work is the major variable in additional cost and production time (welding) is the major variable in savings. Hence the value of total savings is significant higher than the value of total additional costs, the saved production time is the most significant factor when benefits are evaluated.

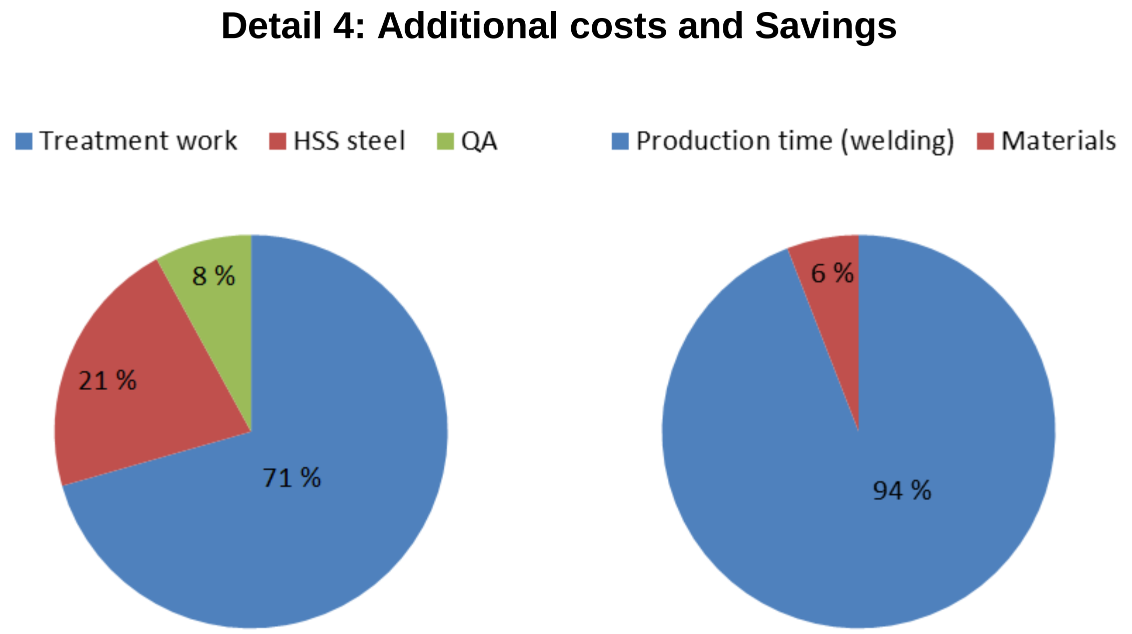


Figure 32. Additional costs (left side) and savings (right side) for Detail 4. Total value of additional costs is 33 € and savings is 453 € per one detail.

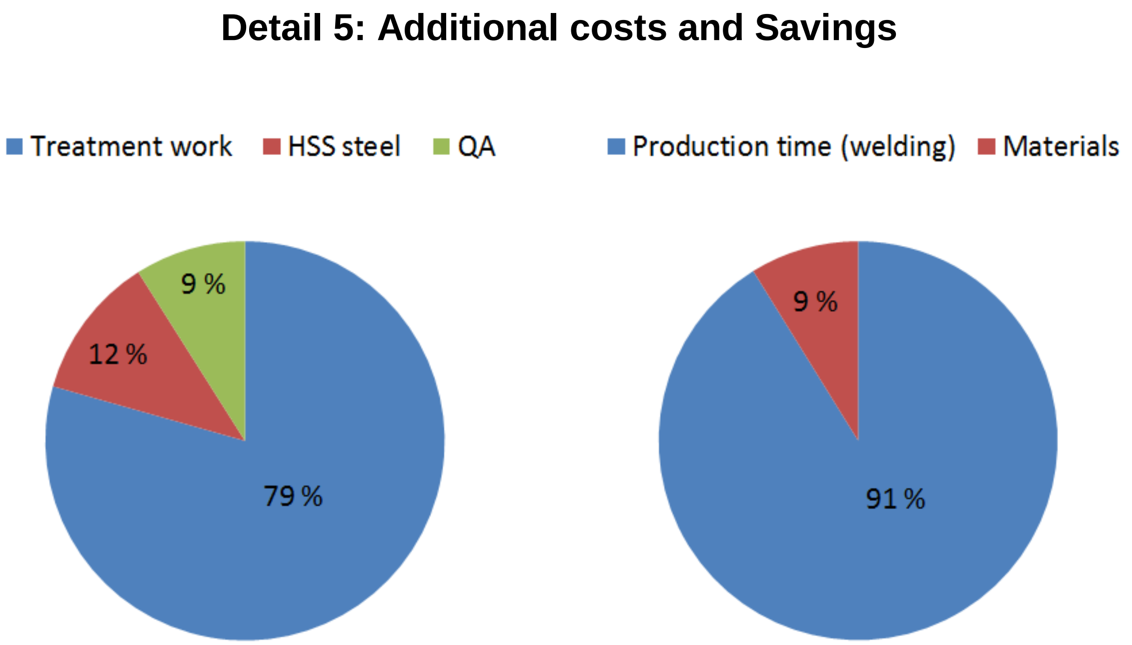


Figure 33. Additional costs (left side) and savings (right side) for Detail 5. Total value of additional costs is 29 € and savings is 809 € per one detail.

From the design aspect benefits can be obtained as well, nevertheless, the value is complex to measure in money. Less detail level analysis may be needed and many local fatigue issues could be solved quickly at the design phase. From the vessel owner point of view, probably no significant costs or benefits are resulted. However, small positive effect for the price may occur.

In conversion and repair project the post-weld treatment methods could be highly valuable as well. Fatigue life extension by peening method for existing structures has been investigated with good results. [49] [38] Fatigue life extension and successful repair of chronic cracking has been obtained in high stressed areas on structural details of offshore and marine installations in service. Continuous crack repair and structural modification were identified expensive whereas the peening treatment offered a cost-efficient solution for the crack repair. Peening was estimated to be approximately 10 times less costly than modification of the structure. [38] If the fatigue life of the existing structures can be extended or fatigue damage reset to zero by post-weld treatment methods, the huge potential for conversion projects can be identified. For example an FPSO converted from the existing tanker includes several details where restoring its original fatigue strength would be highly valuable since less structural modifications for the original structure would be needed. However, more investigation related to restoring the fatigue strength is needed to recognize the full benefit.

As a summary, additional cost and savings highly differs case-by-case. Design and manufacturing aspects should be combined into economic view to maximize net benefits. High strength steels with the post-weld treatment can be seen as a very potential and cost-efficient method to simplify structural geometry in the detail level and hence, obtain savings which can be significant if multiple similar details are accounted. Detail types where the large amount of weld meters is reduced have the largest potential for significant savings. Other way to utilize potential of the investigated methods is to locally improve the fatigue strength of the welded details at the hot spot locations if stresses exceed the allowable ranges.

7 DISCUSSION

This thesis studies the utilization potential of HSS steel in FPSO structures. Apparent benefit is observed, however, it should be remembered that insufficient design cannot be improved by high strength steel and weld treatment in any case. This means that the original fatigue strength has to be already in sufficient level that improved methods could be considered. Classification society American Bureau of Shipping (ABS) states that: "*the calculated fatigue life is to be greater than 2/3 times the design fatigue life years excluding the effects of the improvement techniques*". [50] Similar guidance by the other classification societies in not written in the rules, but is expected.

The guidance between different classifications societies vary as well. Classification society Lloyd's Register gives very similar guidance regarding to fatigue strength improvement such DNV. [41] Fatigue strength improvement factors given by Lloyd's Register are a bit smaller, however, very similar benefits compared to DNV could be obtained. Classification society ABS has much limited guidance regarding the fatigue strength improvement. [50] They permit a factor of 2 on fatigue life by hammer peening or toe grinding whereas DNV permits factors up to 4 with HSS. Nevertheless, classification rules are changing slowly and in the future, the achieved fatigue strength improvement based on the classification rules may increase since more experience exists and practises become more standardized.

Quality assurance and control related issues have important role in development of standardised design practises. The visual inspection alone is not sufficiently effective to maintain quality of fatigue improved welds. Quantitative (groove depth for example) and qualitative (position of groove and lack of any crack-like lines for example) measures can be used for quality control. An accepted procedure for the treatment procedure, which is carefully followed, has seen the most practical quality strategy. More attention for the quality related issues should be paid in the future. Also, several side effects that may occur should be recognized if HSS steels and weld treatment methods are applied.

One side effect related to peening methods is that induced compressive stresses may be relaxed during the remaining service life as a result of high stress peaks due to loading and unloading of FPSO. This phenomenon is not well known so far and it needs further investigation under the variable amplitude loading. Alternatively, geometry improvement methods such as grinding could be considered as well. In some cases also the lack of space for the treatment tool may cause challenges. Hence, for very complex geometries and tight spaces the applicability of the post weld treatment may be limited due to lack of space. This should be considered at the design phase if treatment method is planned to be utilized.

The potential for other purposes such as crack repair and conversion projects have been recognized as well. Local fatigue critical details can be improved by post-weld treatment cost-efficiently and excellent results from the repair of chronic cracking have been experienced. Also the potential for the life extension in conversion projects is significant. If the fatigue life of the existing structures can be extended by post-weld treatment methods, a great benefit could be obtained. For example an FPSO converted from the existing tanker includes several details where restoring its original fatigue strength would be highly valuable since less structural modifications for the original structure would be needed. However, further investigation related to restoring of the original fatigue strength of the details is needed.

8 CONCLUSION

Benefiting from the high strength steel in Floating Production Storage and Offloading unit structures under fatigue loading was investigated. In welded structures, it has been found that the potential of HSS can be utilized better if welds are treated. Hence, post-weld treatment was used with the HSS in order to increase the fatigue strength of investigated details. Hammer peening and High Frequency Mechanical Impact post-weld treatment methods were referred. S-N curves for improved details from the DNV classification rules and literature were used. Significant increase of the fatigue life and maximum allowable stress range was obtained. Based on the analysis the benefits were estimated.

Peening methods were identified as the most potential and applicable for marine and offshore installations. Nevertheless, other improvement methods such as grinding or TIG-dressing could be used as well. S-N data for the other improvement methods presents slightly smaller increase for the fatigue strength, although very similar results would have been found. Based on the findings from the literature, post-weld treatment is commonly used in particular industry fields. In marine and offshore context they are less utilized. However, during the recent years post-weld treatment methods and high strength steels have been noticed in the classification rules for marine and offshore installations as well.

In the scope of this thesis classification rules of DNV were referred to. The current practise follows case-by-case type of approval principle and therefore, classification society has a lot of room how to adapt their rules. Classification society DNV has released improvement factors for un-welded HSS base material as well as for welded structures combined with post-weld treatment methods. The fatigue strength improvement based on the factors given by DNV and IIW are conservative and considerably lower than literature findings present. According to literature S-N data significantly higher allowable stress range could be achieved and hence, obtain even higher benefits.

Use of high strength steels is typically driven by weight saving. However, in the scope of this thesis the obtained weight saving was not the first priority. Instead of weight, cost-savings were reached by simplifying the structural geometry. The results indicate that although the highly fatigue optimized geometry is turned into simple cost optimized geometry the same fatigue strength can be remained. Hence, significant decrease in the production costs could be achieved. In the future actual values should be measured in production in order to determine realistic net benefit and make accurate conclusions. On the other hand, if local stress concentrations are causing the exceedance of the allowable stress range, fatigue strength of the weld toe region could be improved by HSS and weld treatment. Therefore design hours could be saved and high cost modifications avoided. It was also found that the increase of the nominal stress range is the same with the sufficient precision for each detail investigated. Therefore, it can be assumed that the resulted perceptual increase in each condition can be used as rough estimation factor for the stress range increase for similar cases.

It has been found that if the fatigue strength is increased locally by weld improvement at the certain hot spot area which is the most fatigue critical, the problem may switch over to the other hot spot location which becomes the most critical. This effect may happen for example to the typical stiffener support (Detail 4) if hot spots at the weld toe are improved and hot spot at base material at the scallop rounding may become critical. Therefore all hot spot locations should be carefully considered if stress range is increased.

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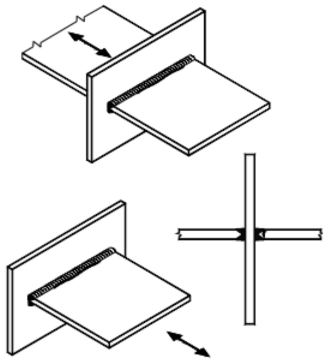
APPENDICES

Appendix A – Classification of welded joint, given in DNV RP-C203 [25]

F	1. 	1.Full penetration butt welded cruciform joint	1.: — Inspected and found free from significant defects. The detail category is given for: — Edge distance ≥ 10mm — For edge distance < 10mm the detail category shall be downgraded with one SN-curve

Appendix B – S-N curve parameters for air (above) and for seawater + cathodic protection (below) given in DNV-RP-C203 [25]

4.3.5 Hot spot S-N curve

It is recommended to link the derived hot spot stress to the D- curve.

Table 2-1 S-N curves in air

S-N curve	*$N \le 10^7$ cycles*		*$N > 10^7$ cycles* $\log \bar{a}_2$	*Fatigue limit at 10^7 cycles *)*	*Thickness exponent k*	*Structural stress concentration embedded in the detail (S-N class), ref. also equation (2.3.2)*
	m_1	$\log \bar{a}_1$	$m_2 = 5.0$			
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.15	
C1	3.0	12.449	16.081	65.50	0.15	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50
T	3.0	12.164	15.606	52.63	0.25 for SCF $\le$ 10.0 0.30 for SCF >10.0	1.00
*) see also section 2.11						

Table 2-2 S-N curves in seawater with cathodic protection

S-N curve	*$N \le 10^6$ cycles*		*$N > 10^6$ cycles* $\log \bar{a}_2$	*Fatigue limit at 10^7 cycles*)*	*Thickness exponent k*	*Stress concentration in the S-N detail as derived by the hot spot method*
	m_1	$\log \bar{a}_1$	$m_2 = 5.0$			
B1	4.0	14.917	17.146	106.97	0	
B2	4.0	14.685	16.856	93.59	0	
C	3.0	12.192	16.320	73.10	0.15	
C1	3.0	12.049	16.081	65.50	0.15	
C2	3.0	11.901	15.835	58.48	0.15	
D	3.0	11.764	15.606	52.63	0.20	1.00
E	3.0	11.610	15.350	46.78	0.20	1.13
F	3.0	11.455	15.091	41.52	0.25	1.27
F1	3.0	11.299	14.832	36.84	0.25	1.43
F3	3.0	11.146	14.576	32.75	0.25	1.61
G	3.0	10.998	14.330	29.24	0.25	1.80
W1	3.0	10.861	14.101	26.32	0.25	2.00
W2	3.0	10.707	13.845	23.39	0.25	2.25
W3	3.0	10.570	13.617	21.05	0.25	2.50
T	3.0	11.764	15.606	52.63	0.25 for SCF $\le$ 10.0 0.30 for SCF >10.0	1.00
*) see also 2.11						

Appendix C – Stress Concentration factors and S-N curve to be used for joints with gusset plates, given in DNV-RP-C203. [25]

3.3.12 Stress concentration factors for joints with gusset plates

Insert gusset plates are sometimes used in joints in topside structures to connect RHS and tubular members. Reference is made to Figure 3-19. When such connections are subjected to dynamic loading a full penetration weld between the member and the gusset plate is preferred. Otherwise it is considered difficult to document the fatigue capacity for fatigue cracking starting from the weld root. In dynamic loaded structures it is recommended to shape the gusset plate in such a way that a smooth transfer of stress flow from the member into the gusset plate is achieved; ref. Figure 3-19 a).

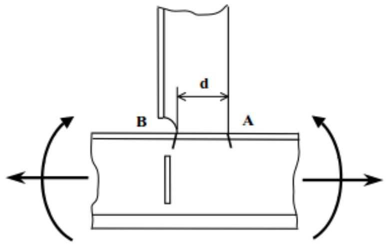
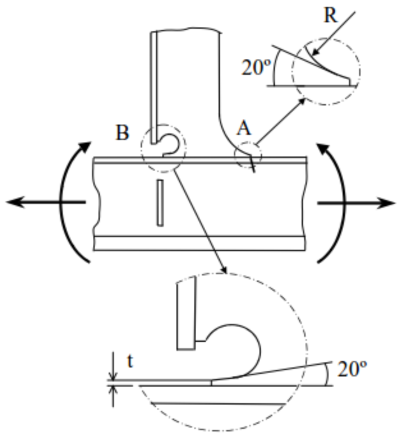
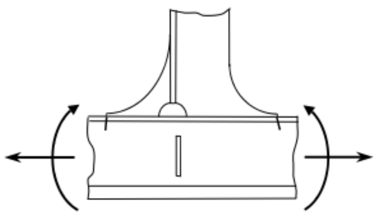
Where a reliable fatigue life is to be documented it is recommended to perform finite element analysis if the geometry is significantly different from that shown in Figure 3-19 b). The stress concentration factors in Table 3-1 are derived from finite element analysis using shell elements. Then the hot spot stress can be combined with the D-Curve. The stress concentration factor for tubular member is simply derived by scaling the results from that of RHS by $\pi/4$ for the same thickness. Using shell elements for such analysis provides conservative stress concentration factors as compared with use of three-dimensional elements with modelling also of the fillet weld. (It is here assumed that a fillet weld also can be used on the outside on a full or partial penetration weld). In a relevant example the resulting SCF using a model with three-dimensional elements was only 0.70 of that from analysis using a shell model. Thus the SCFs in Table 3-1 might be further reduced if necessary.

Table 3-1 Stress concentration factors for joints with gusset plate

Geometry	*SCF*
RHS 250 × 16 with favourable geometry of gusset plate	2.9
RHS 250 × 16 with simple shape of gusset plate	3.8
Ø250 × 16 with favourable geometry of gusset plate	2.3
Ø250 × 16 with simple shape of gusset plate	3.0

Appendix D – Stress Concentration Factors for stiffener supports given in DNV RP-C206. [42]

Table B-2 K-factors for stiffener supports

Geometry	*K-factor*	
B-2.1 	For supporting members welded to stiffener flange:	
	Axial stress in the longitudinal direction At point A: $K_g = 1.33 \quad d \leq 150$ $K_g = 1.40 \quad d > 150$ At point B: $K_g = 1.33 \quad d \leq 150$ $K_g = 1.40 \quad d > 150$	Bending due to lateral load At points A and B: $K_g = 1.60$
	Point A denotes the side of the supporting member and point B denotes the side opposite. For supporting members welded to stiffener web by overlap weld, the above factors shall be multiplied by a factor 1.15.	
B-3.3 	For soft nose bracket toes with a radius greater than 200 mm and soft heels in scallops with a radius greater than 30 mm:	
	Axial stress in the longitudinal direction At point A: $K_g = 1.33 \cdot \left(\frac{60}{R}\right)^{0.05}$ At point B: $K_g = 1.40 \cdot \left(\frac{60}{R}\right)^{0.05}$	Bending due to lateral load At point B: $K_g = 1.73 \cdot \left(\frac{60}{R}\right)^{0.05}$
	For supporting member welded to stiffener, flange only. It is assumed that the weld is kept clear of flange edge.	
B-3.4 	For soft nose bracket toes with a radius greater than 200 mm: $K_g = 1.40\left(\frac{60}{R}\right)^{0.05}$ R = radius in mm of soft nose or heel For supporting member welded to stiffener, flange only. It is assumed that the weld is kept clear of flange edge.	

Appendix E – Allowable hot spot stress ranges

Detail 1: Flexible topside support

Hot spot stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	114,9	139,0	161,1	221,6
355	114,9	151,6	161,1	253,2
550	114,9	151,6	161,1	284,9

Detail 2: Helideck support gusset joint

Hot spot stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	121,3	146,7	168,5	233,9
355	121,3	160,0	168,5	267,3
550	121,3	160,0	168,5	300,7

Detail 3: Fatigue optimized stiffener support

Hot spot stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	122,9	148,6	170,7	236,9
355	122,9	162,1	170,7	270,7
550	122,9	162,1	170,7	304,6

Detail 4: Typical stiffener support

Hot spot stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	122,9	148,6	170,7	236,9
355	122,9	162,1	170,7	270,7
550	122,9	162,1	170,7	304,6

Detail 5: Simplified stiffener support

Hot spot stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	122,9	148,6	170,7	236,9
355	122,9	162,1	170,7	270,7
550	122,9	162,1	170,7	304,6

Appendix F – Allowable nominal stress ranges

Allowable nominal stress ranges for each calculated case.

Detail 2: Helideck support gusset joint

Nominal stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	52,7	63,8	73,3	101,7
355	52,7	69,6	73,3	116,2
550	52,7	69,6	73,3	130,7

Detail 3: Fatigue optimized stiffener support

Nominal stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	100,7	121,8	139,9	194,2
355	100,7	132,9	139,9	221,9
550	100,7	132,9	139,9	249,7

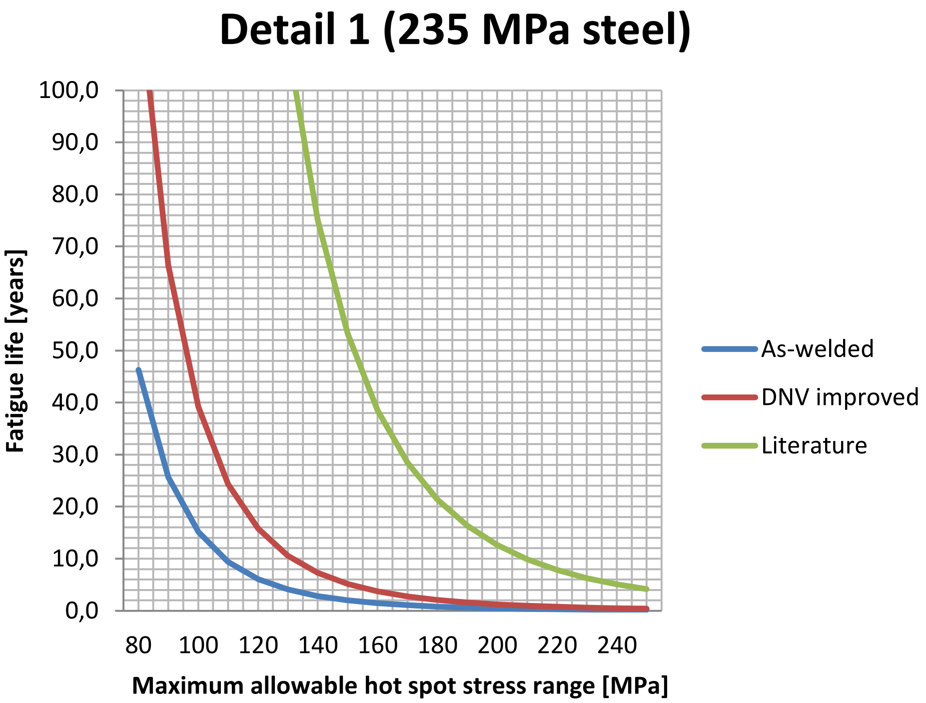
Detail 4: Typical stiffener support

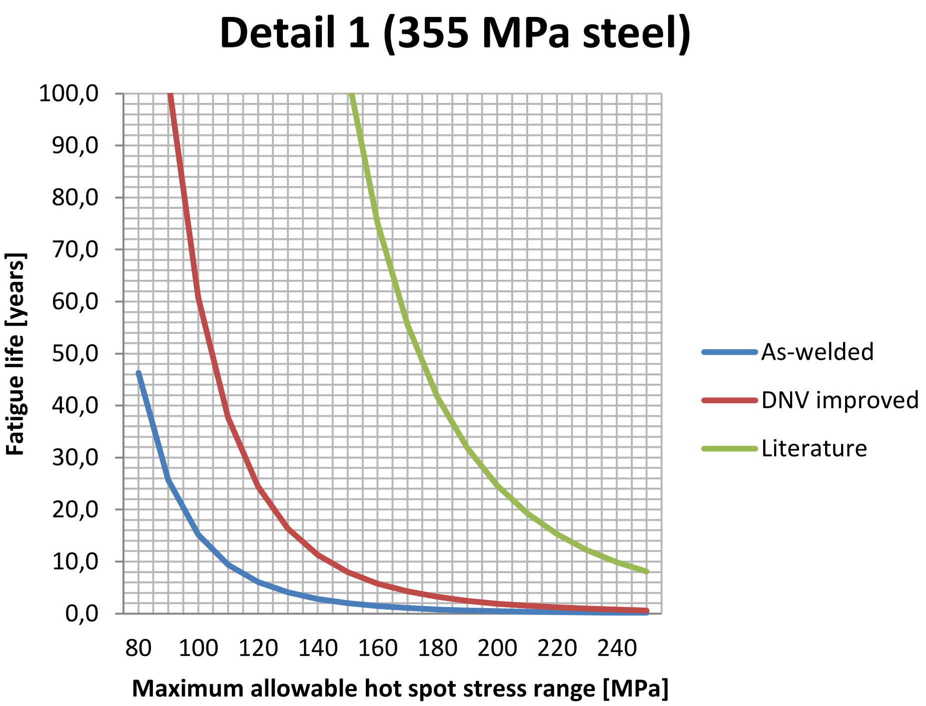
Nominal stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	80,3	97,1	111,6	154,8
355	80,3	106,0	111,6	177,0
550	80,3	106,0	111,6	199,1

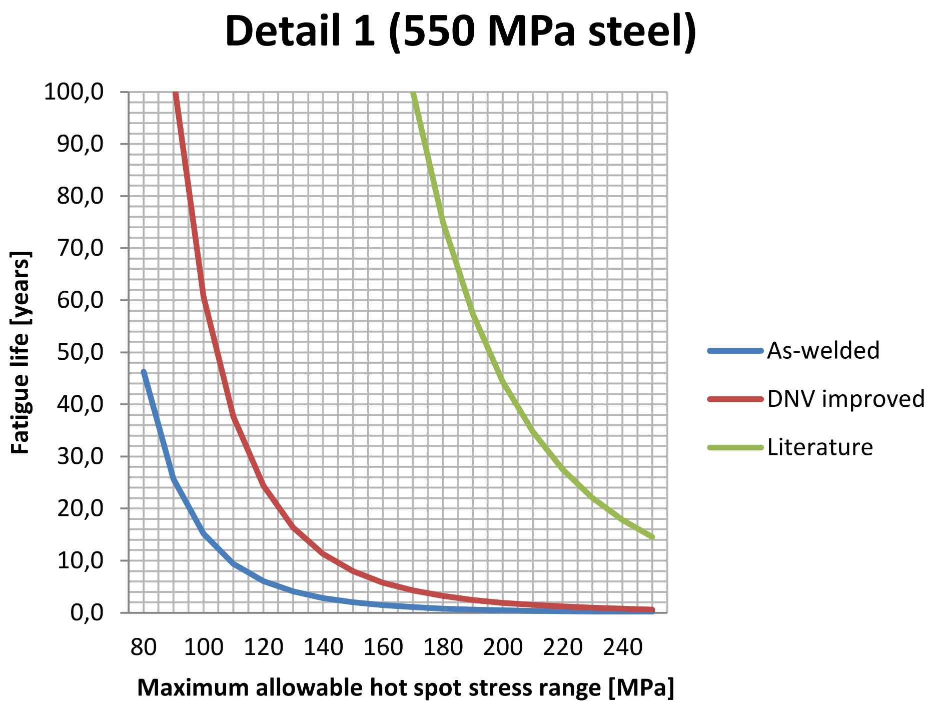
Detail 5: Simplified stiffener support

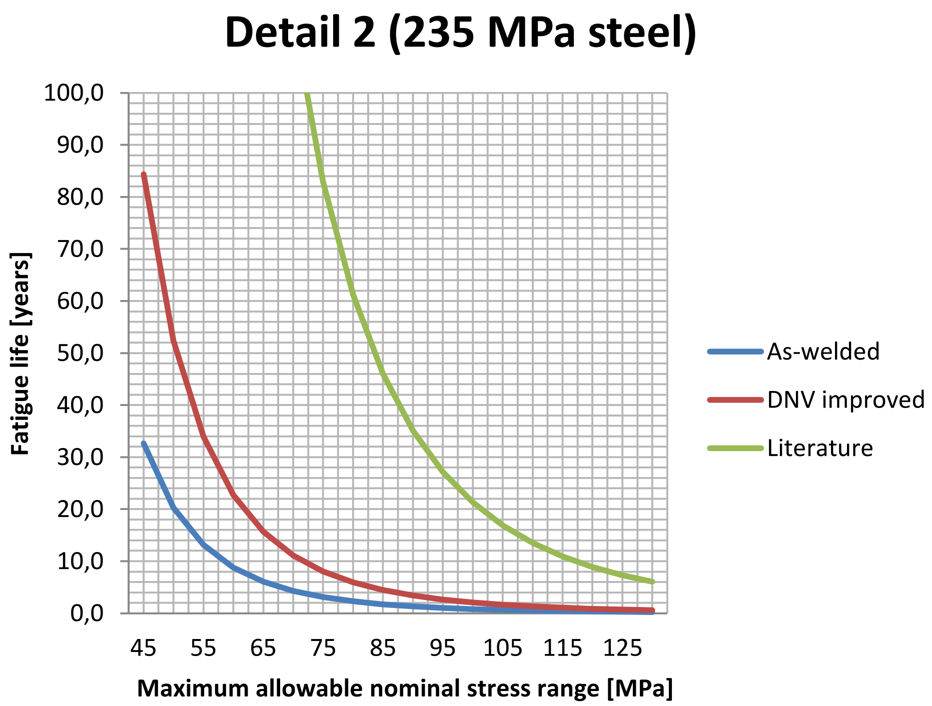
Nominal stress range [Mpa] when D = 1; Fatigue life = 25 years				
Yield strength	As-welded	DNV improved	DNV C-curve	Literature
235	76,8	92,9	106,7	148,1
355	76,8	101,3	106,7	169,2
550	76,8	101,3	106,7	190,4

Appendix G – Fatigue life charts resulted in the fatigue analysis. For the Detail 1 fatigue life is presented in relation to the maximum allowable hot spot stress and for other details to maximum allowable nominal stress.

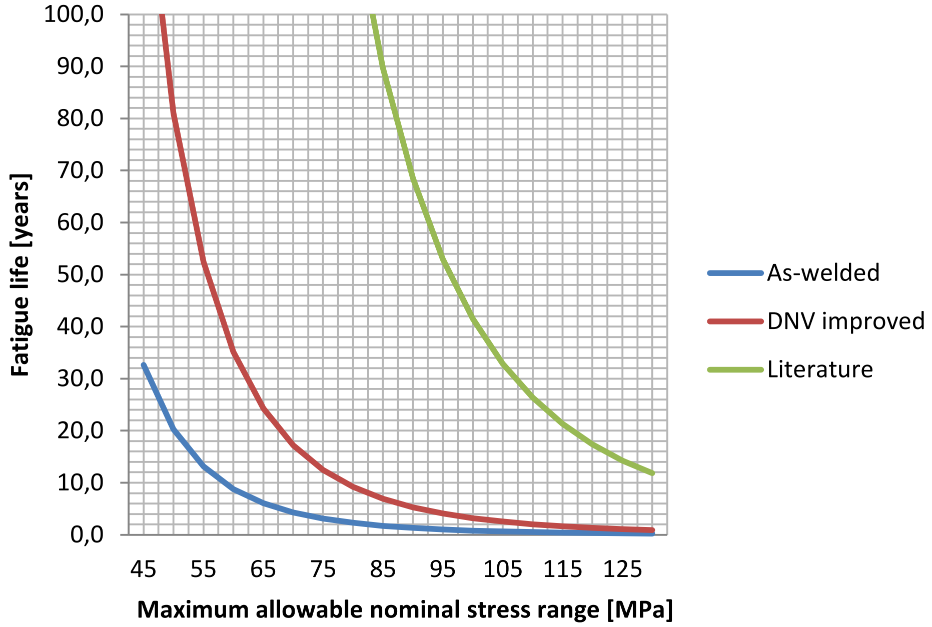




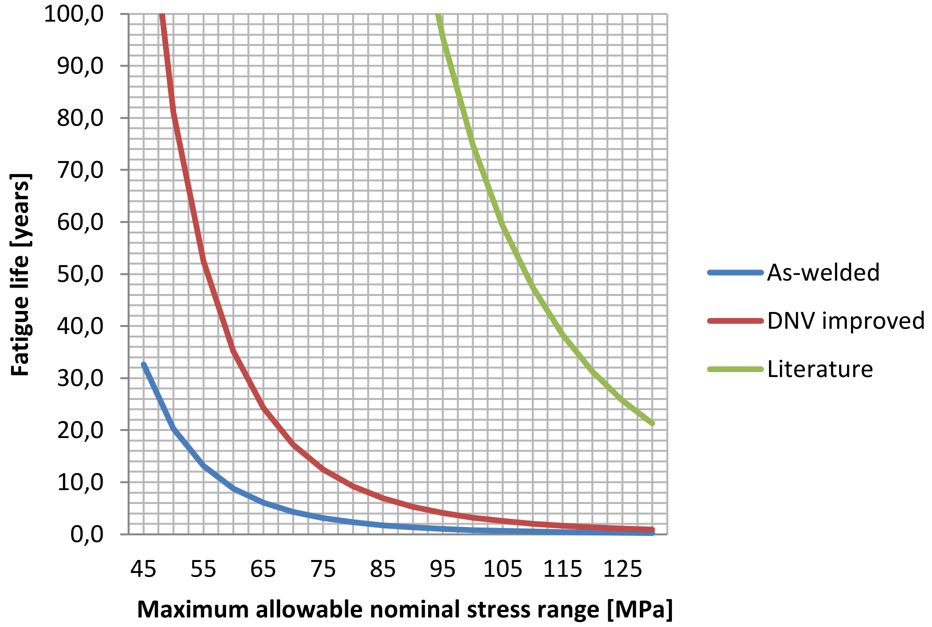

Detail 1 (550 MPa steel)
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
Fatigue life [years]
80
100
120
140
160
180
200
220
240
Maximum allowable hot spot stress range [MPa]
As-welded
DNV improved
Literature

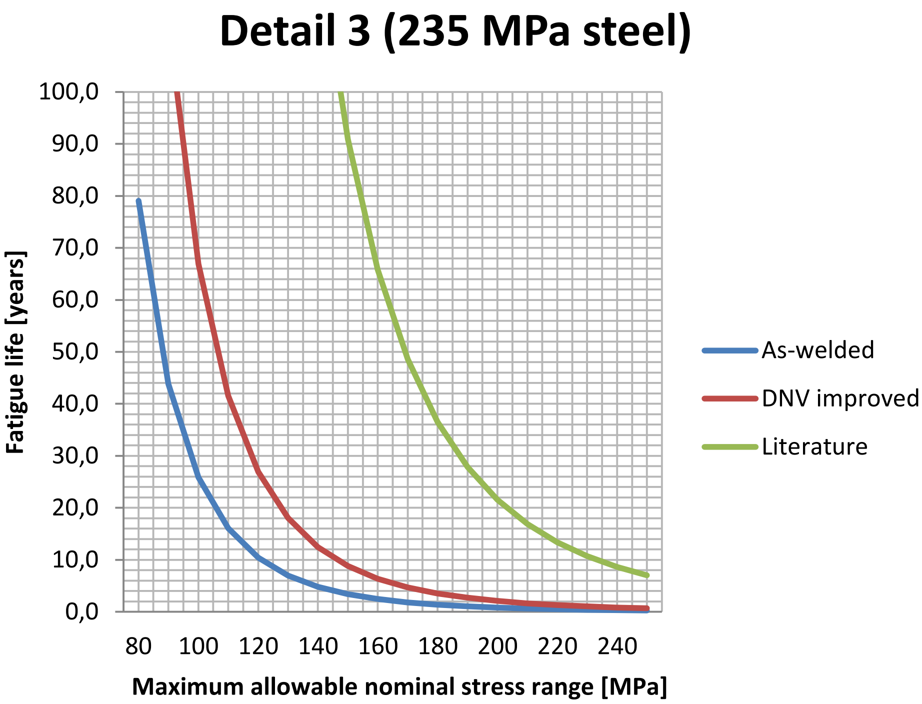

Detail 2 (235 MPa steel)
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
Fatigue life [years]
45
55
65
75
85
95
105
115
125
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

Detail 2 (355 MPa steel)

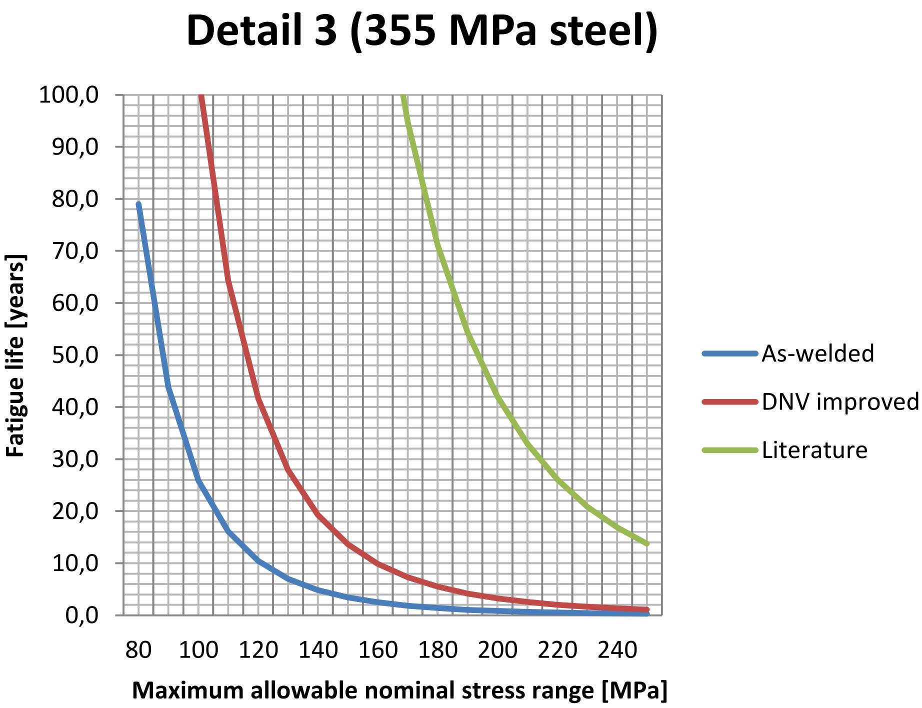


Detail 2 (550 MPa steel)

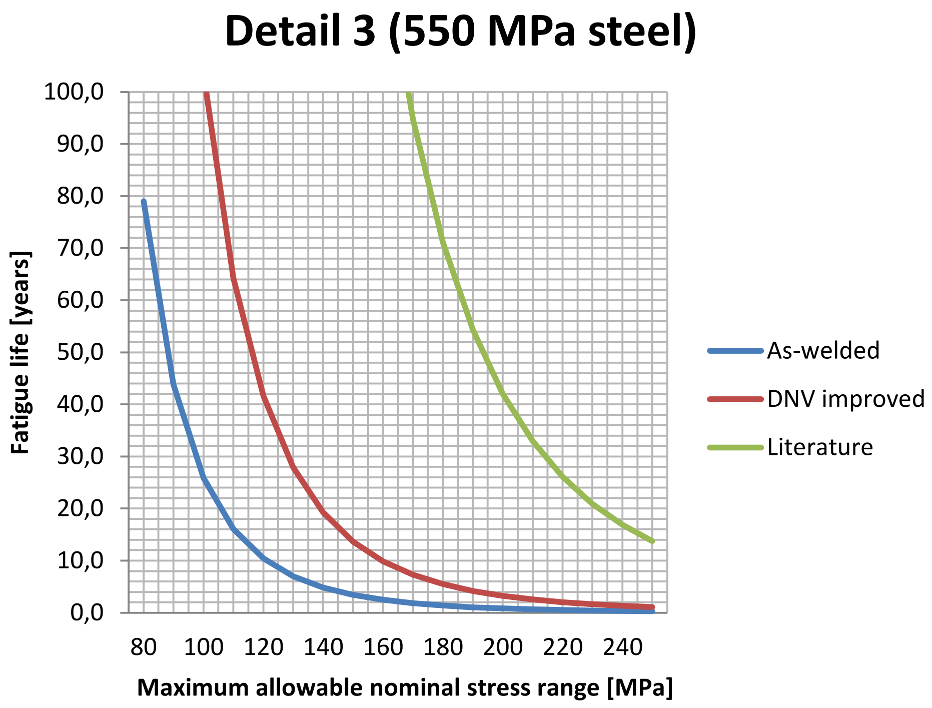




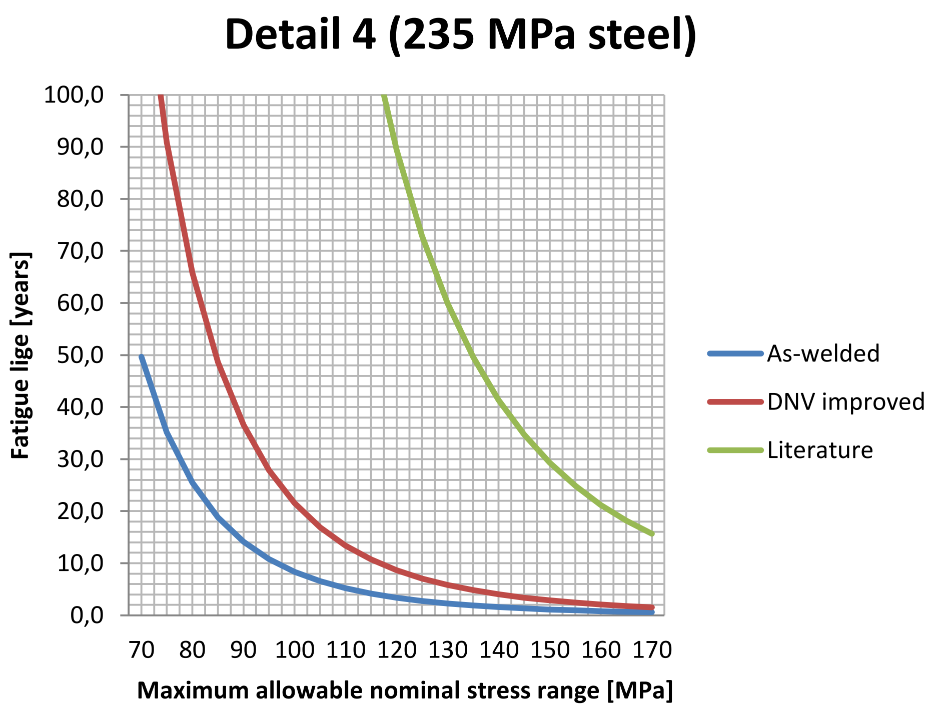
Detail 3 (235 MPa steel)
Fatigue life [years]
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
80
100
120
140
160
180
200
220
240
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature



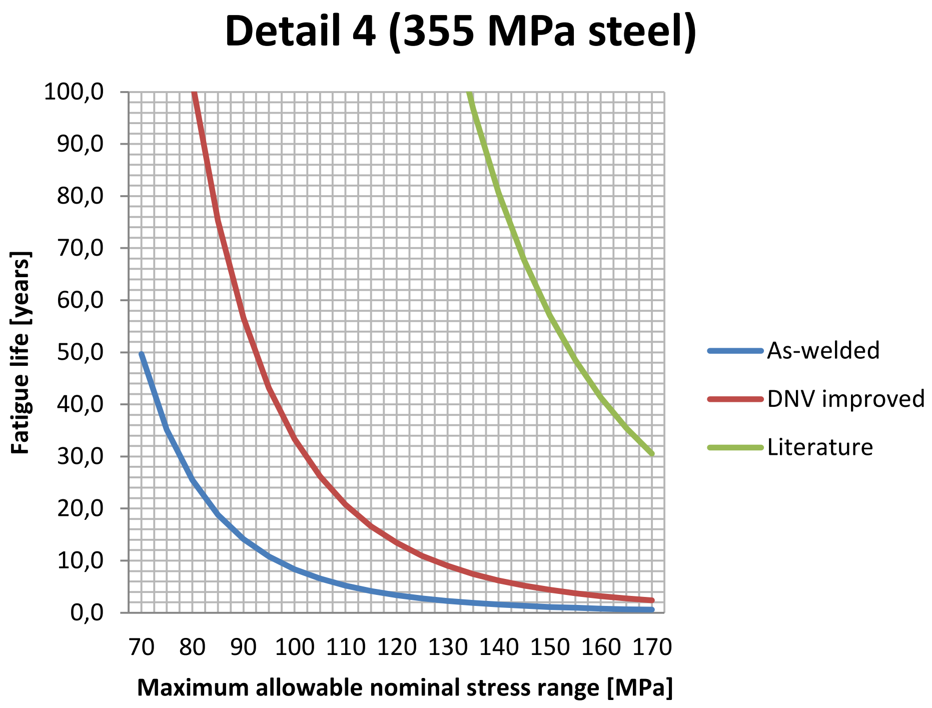
Detail 3 (355 MPa steel)
Fatigue life [years]
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
80
100
120
140
160
180
200
220
240
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

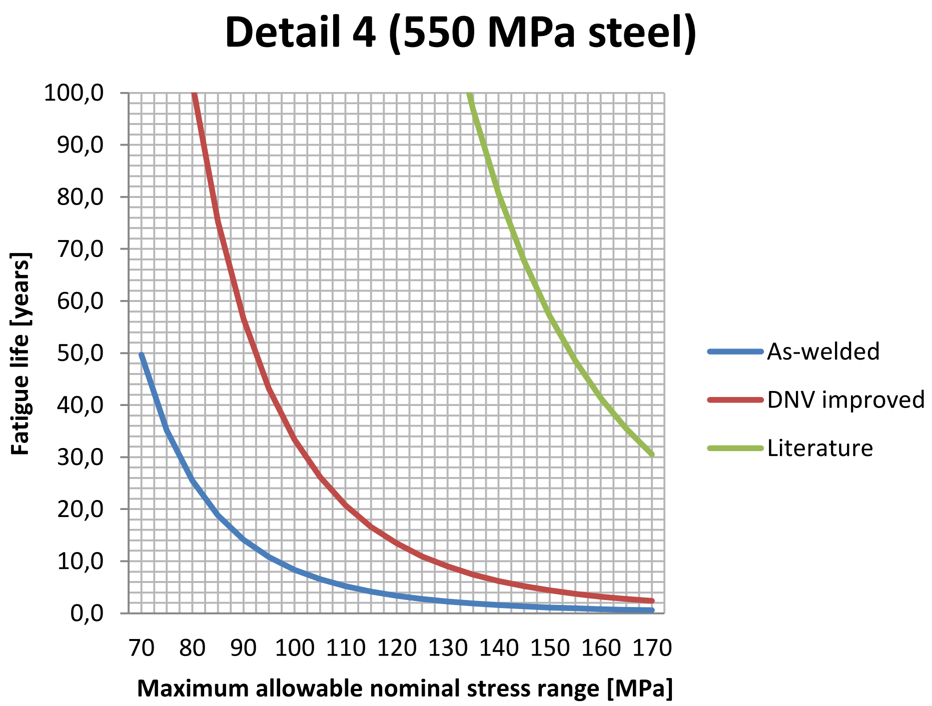


Detail 3 (550 MPa steel)
Fatigue life [years]
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
80
100
120
140
160
180
200
220
240
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

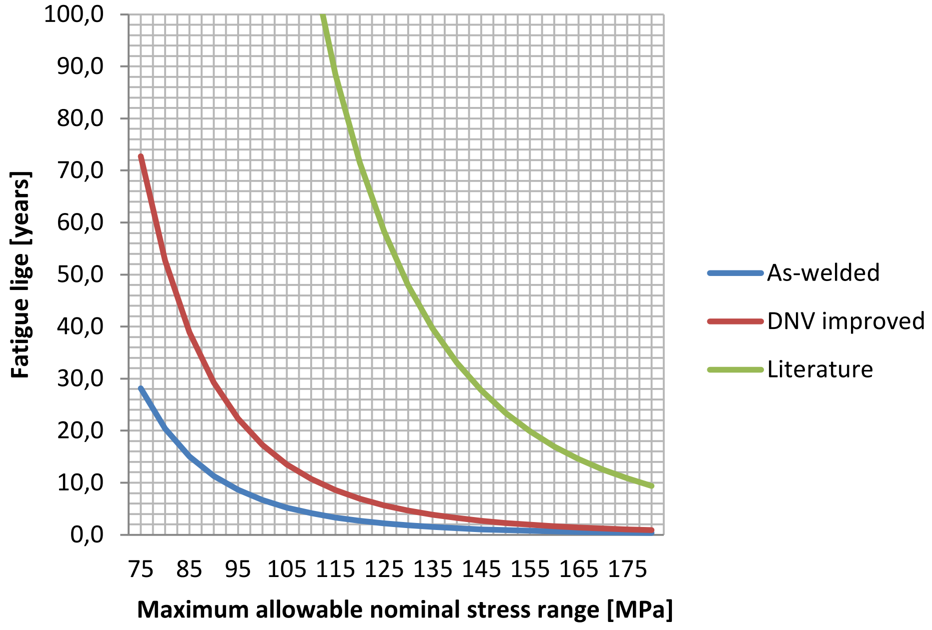


Detail 4 (235 MPa steel)
Fatigue lige [years]
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
70
80
90
100
110
120
130
140
150
160
170
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

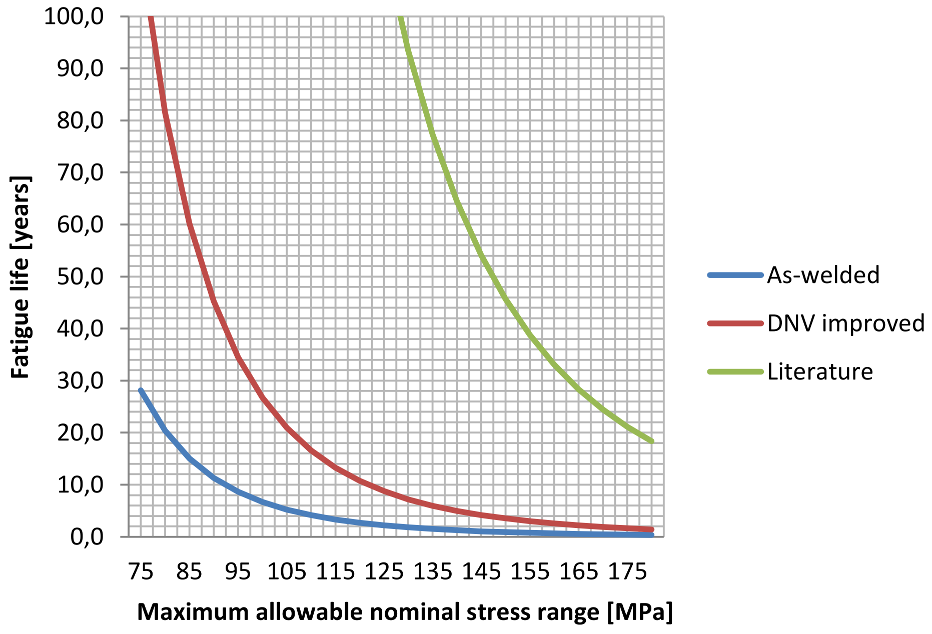

Detail 4 (355 MPa steel)
Fatigue life [years]
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
70 80 90 100 110 120 130 140 150 160 170
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

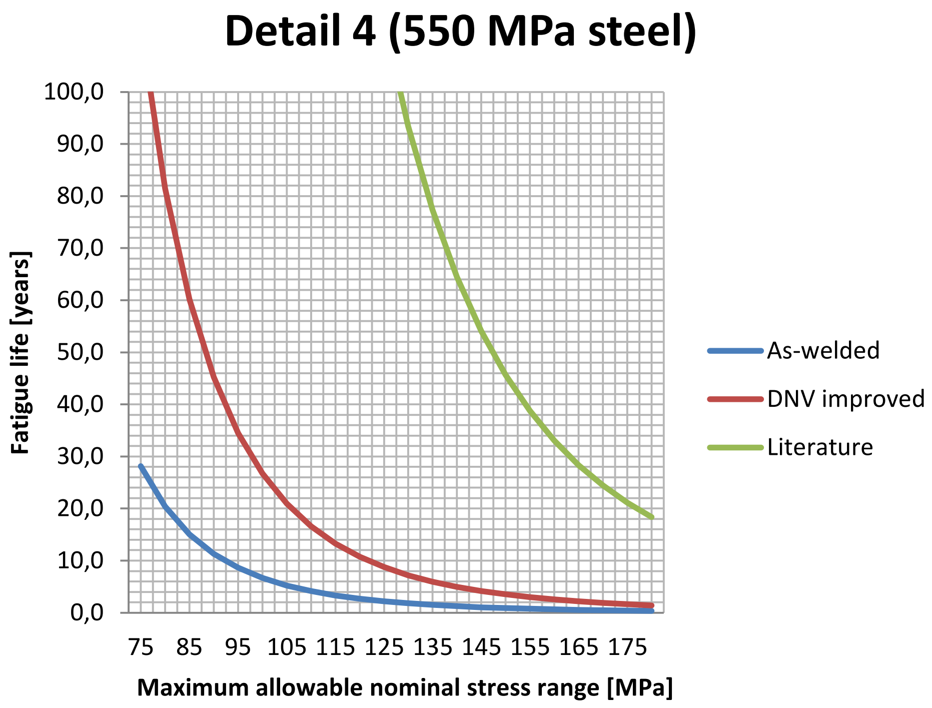

Detail 4 (550 MPa steel)
Fatigue life [years]
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
70 80 90 100 110 120 130 140 150 160 170
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

Detail 4 (235 MPa steel)



Detail 4 (355 MPa steel)





Detail 4 (550 MPa steel)
100,0
90,0
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
Fatigue life [years]
75 85 95 105 115 125 135 145 155 165 175
Maximum allowable nominal stress range [MPa]
As-welded
DNV improved
Literature

Appendix H – Cost-Benefit Analysis Breakdown per one detail

Detail 4: Additional costs

Type	Min	Average	Max	Unit
Treatment work	15,4	23,2	31,1	€
HSS steel	4,6	7,1	9,5	€
QA	0,8	2,6	4,5	€
SUM	**20,7**	**32,9**	**45,1**	**€**

Detail 4: Savings

Type	Min	Average	Max	Unit
Production time (welding)	228,7	426,2	623,7	€
Materials	22,7	26,8	30,9	€
SUM	**251,3**	**453,0**	**654,6**	**€**

Detail 5: Additional costs

Type	Min	Average	Max	Unit
Treatment work	15,4	23,2	31,1	€
HSS steel	2,2	3,4	4,6	€
QA	0,8	2,6	4,5	€
SUM	**18,3**	**29,2**	**40,2**	**€**

Detail 5: Savings

Type	Min	Average	Max	Unit
Production time (welding)	396,0	738,0	1080,0	€
Materials	60,4	71,4	82,4	€
SUM	**456,4**	**809,4**	**1162,4**	**€**